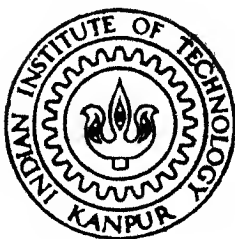# A Novel Control Strategy For A Variable Series Compensated AC Line Operating In Parallel With A DC Line

by

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February 1997

A Novel Control Strategy For A Variable Series Compensated AC Line Operating In Parallel With A DC Line

A Thesis submitted
in partial fulfilment of the requirements
for the Degree of
MASTER OF TECHNOLOGY

by

ALOK KUMAR MITTAL

to the

Department of Electrical Engineering
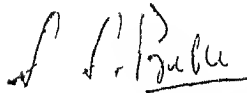Indian Institute of Technology, Kanpur
February 1997

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CERTIFICATE

It is to certify that this M Tech thesis work entitled A Novel Control Strategy for a Variable Series Compensated AC Line Operating in Parallel with a DC Line *has been carried out by* **Alok Kumar Mittal** *under our supervision and has not been submitted elsewhere for a degree*
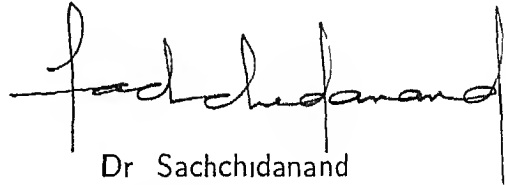

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Dedicated to

My Parents

Abstract

With increasing demands made on existing transmission systems power systems are becoming highly stressed This deteriorates the system s transient and dynamic performance To deal with it, controllable devices like FACTS(Flexible AC Transmission Systems) and HVDC links will be increasingly utilized Future power systems will have many such controllable devices In an integrated system, their interaction will be critical Without any co ordination in their operation, the control interaction may be detrimental to system security

This thesis adresses such issues related to parallel operation of an HVDC link with a variable series compensated AC line where the device used for series com pensation is TCSC (Thyristor Controlled Series Capacitor) The control strategies possible are investigated It is shown that if the controls of HVDC link and TCSC are not co ordinated no significant advantage will be obtained compared to an uncontrolled line It may even have a negative effect on system operation Here a control strategy is proposed for TCSC which does not come in conflict with HVDC controls The controller proposed here can be realised with locally measurable signals The suitable values of control parameters are found for this controller Systems's performance is evaluated for a wide range of system disturbances, using PSCAD/EMTDC The control strategy used here shows a marked improvement in transient stability compared to an uncontrolled line

Acknowledgements

the sunset everv time It was alwavs amusing to talk in *tapori* language with Moogi my other friend I am wondering whether to thank him for spoiling mv grammar Last but not the least, my thanks to Manoj for giving me constant encouragement and offering all the help Listening to his *hasya kavitayen* was a small price to pav for his friendship

I also thank mv friends Amol and Arvind for providing good companv

Contents

List of Figures

Chapter 1

Introduction

1 1   General introduction

With ever increasing power demand tapping of new resources has become necessary
Most of the new generation is likely to be far away from load centres   Transmission
of power from generating centres to distant load centres will be required As increase
in transmission capablities becomes necessary power system engineers will face new
challenges in fields of planning operation control and stability of power systems
The constraints imposed by existing transmission system and performance expected
from the upgraded system will dictate the choice of new configuration Enviormental
concerns are also becoming important now But above it all economics will be the
dominant factor

As level of power transfer over existing corridors increases systems   transient
and dynamic performance deteriorates   To deal with it new schemes must have
an element of controllability So technologies like HVDC and FACTS (Flexible AC
Transmission Systems) are becoming important FACTS which is relatively a new
technology is gaining wide spread acceptance now This is because installation of
FACTS devices on existing AC transmission systems makes them controllable to
some extent

Concept of FACTS was given by EPRI (Electrical Power Research Institute)
of USA FACTS is based on the use of power electronics components to enhance

controllability and power transfer capabilities of AC transmission systems Some of the important FACTS devices are [1]

1. SVC(Static VAR Compensator) Shunt connected Used mainly for voltage control

2. STATCOM(Static Compensator) - Shunt connected Used mainly for voltage control

3. TCBR(Thyristor Controlled Braking Resistor) Shunt connected Used mainly for transient stabilty control

4. TCPST(Thyristor Controlled Phase Shifting Transformer) - Series connected Used mainly for power flow control and stabilty improvement

5. TCSC(Thyristor Controlled Series Capacitor) Series connected Used mainly for power flow control stabilty improvement and SSR damping

Also all these devices except TCBR can have a supplementary control for improving system damping

This thesis looks into the issues related to parallel operation of AC and HVDC line where AC line is variable series compensated by TCSC

1 2 Practical relevance of the system under study

When large power is supplied from one area to another and increase in transmission capacity is required due to addition of generation in the supplying area and increased demand in receiving area, choices available to system planners are

- Some high voltage AC lines may exist to supply the previous demand In such a case, one option is to lay new AC lines But this will require huge investment and may not be possible due to enviormental concerns An alternative option will be to series compensate the existing AC lines to increase their power transfer capabilty

2

If the series compensation is fixed it will create two problems Firstly it will not offer any controllability So the performance under contingencies like faults outage of parallel lines sudden change in power level etc will be unacceptable Since large power transfers are involved system security is very important The line flows affect both the areas receiving as well as supplying The second problem with fixed series compensation is SSR (sub-synchronous resonance) To overcome these problems controllable series compensation becomes necessary TCSC is well suited for the purpose

- A more common case is of an HVDC link existing in parallel with high voltage AC line to meet the earlier demand A single HVDC link without any parallel AC line is improbable due to natural growth patterns of power system (except in case of asynchronous systems) Also many times a single HVDC link working as a critical line may be undesirable This is because of the very fast response of DC link to system contingencies like faults under which it reduce the power flow to zero very rapidly This may endanger the stability of both the areas To deal with it special controls are required Another disadvantage with DC link is that it does not provide any synchronising torque and as a frequency insensitive load may produce negative damping Also it may cause voltage instability [2]

In case of a parallel AC DC link to meet the new transmission capacity required, two options exist with system planners The first one is to upgrade the existing HV DC link to carry the additional power This will be very costly since not only will it need changes in converter and DC line but will also need changes in AC side filters and reactive compensation Also as discussed above it will create some additional problems Although the DC link offers excellent controllability for steady state power scheduling and can provide damping of AC system with modulation the same cannot be said for its performance under faults Even for power flow scheduling it needs co ordination with generators

A better option will be to variable series compensate the existing AC lines with TCSC It will boost the power transfer capacity as well as provide controllability, both under steady state and transients Also TCSC performance

3

is inherently very good for SSR mitigation and with an auxiliary control it has been found to be best for damping of electromechanical oscillation [3 4]

An HVDC link in parallel with a variable series compensated line will be a very potent combination It will boost up the power transfer capability over the corridor provide fast control over the power flow and give satisfactory performance under contingencies like faults Also because of two controllable lines the link may be assigned multiple control objectives

In near future such a system may come into existence The scope for such a system exist in pacific intertie and IPP in western USA In India too scope exist for Rihand Dadri link

1 3   Objective of the thesis

This thesis investigates control interactions and co ordination strategies in case of parallel operation of an HVDC link with a variable series compensated high voltage AC line The device used for variable series compensation is TCSC In this thesis system is suitabally modelled with detailed representation of both HVDC link and the VSC(variable series compensated) AC line

The main task of this thesis is to develop suitable control strategies for both VSC and HVDC link It is to be ensured that the controls for both do not clash They should improve the system performance The controls should be able to track any change in their reference values Also they should improve the system stability under fault conditions The suitable values of control parameters needs to be found for these objectives The control interactions have to be studied under various conditions

1 4   Literature review

As the number of controllable devices increase in a power system their interaction becomes important Fast power electronics devices has the potential for detrimental interaction with other devices [5]   [6] discusses such control interaction for two

parallel AC lines both with variable series compensation It is demonstrated that if controllers for both acts in a co-ordinated manner it will improve the system performance significantly In [5] the interaction between TCSC and SVC is studied It shows that interaction exists between voltage input auxiliary control of TCSC, the series compensated AC system resonance and SVC controls It suggests proper filtering and change in control strategy to avoid problems associated with this interaction

Unfortunately the problem of control interaction and co-ordination has not re ceived the attention it deserves Literature is very scarce on large signal interaction although a number of papers have been published on small signal interaction

The concept of using HVDC link to stabilize a parallel AC line is very old [7] Most of such schemes use current modulation on the DC link [2 8] A wealth of liter ature is available on using TCSC auxiliary control for damping of electromechanical oscillation [3 9 10] It has been found to give a far better performance compared to SVC or PAR Also, its action is not dependent on its location [3] In [11] a scheme for TCSC use for transient stability improvement is presented

TCSC is a new device and there is considerable interest in power system commu- nity about it In [12], its basics and performance aspects like impedence character istics harmonics response time and the effect of its reactor size are discussed [13 14 15] discusses TCSC modelling for stability studies In [16] rating consideration for TCSC are discussed [17] discusses the various issues related to TCSC installed at Kaventa in Arizona USA In [4], the TSCS response under SSR frequencies is discussed It is shown that TCSC detunes the SSR since it presents an inductive resistive impedance at SSR frequencies

1 5 Summary of the work reported in this thesis

A chapterwise summary is as follows

Chapter 2 looks into the need of co-ordinated control and control strategies for the parallel operation of variable series compensated AC line and HVDC link

In Chapter 3, system is modelled on PSCAD A detailed discription of system

and its control is given

In Chapter 4 simulation studies are carried out to assess the performance of the control strategies under various conditions

Finally, Chapter 5 gives the conclusions and suggestions for further work

Chapter 2

Control Strategies for a parallel AC-DC link

2 1   Introduction

Installation of FACTS devices and increasing use of HVDC links while solving many of the existing problems will pose some new problems as well FACTS devices and HVDC are very fast acting Without proper co ordination of their controls these devices may adversely affect overall operation of power systems although they may solve local problems

2 2   Effect of a controllable line in SMIB system

When a controllable line supplies power from a generating station to a very large power system which can be modelled as an infinite bus, it has to work under certain constraints The most basic of these constraints is the constant mechanical input to the generator for the duration of transient, since the governor action is quite slow So the power on the line should correspond to the mechanical input to the generator If the reference value for the controller on the line is such that the corresponding power flow does not correspond to the mechanical input, the generator will start either accelerating or decelerating After it, two possibilities are there

7

1 The controller output will hit one of its limits since given a constant mechanical input of the generator it can not achieve its reference value After this the system will settle down to a steady state in some time The hitting of limits is undesirable since there is no controllability left in one direction to deal with further contigencies

2 If the control action is very fast system will fice a big jerk and it may even lose stability

The fundamental point is that the control action should be such that a proper operating point exists for the system The control response should be reasonably fast to meet the system contigencies like faults but it should not be so fast as to cause a large jerk to the system in case of reference changes which mav cause the system to lose stability This requirement is more severe in case of very fast device response, like an HVDC link

So the control strategy has to be decided judiciously in case of a controllable line in an SMIB system The requirements become more severe in case of two parallel lines where both lines are controllable

2 3   Effect of multiple controllable lines

An interesting case arises when two or more parallel lines are supplying power from one point to another, where some or all of the lines are controllable The controllable lines may be HVDC lines or AC lines with FACTS devices installed on them The overall objective is to supply a given amount of power which has to be decided in conjunction with power generation and demand in both areas and to ensure system security under transients as well as in steady state Here the situation is more complex compared to the case of single controllable line, since the total power flow over the corridor should correspond to mecanical input to generators So the controllers on the individual line not only need to consider the mechanical input to the generators, but have to co ordinate among themselves If there is no co-ordination among controllers for the parallel lines the controllers on these lines may set a reference value for which no operating point may exist Under such cases,

8

either one or more controllers will hit their limits Under extreme cases system may even lose stability Because of the multiple controllers, system will behave in a unpredictable and erratic way

There are two solutions to this problem

1 Use of a master control

2 Use of non conflicting local controls

2 3 1   Use of a master control

The first approach to solve the co ordination problem is to have a master controller which will assign the tasks to individual controllers in such a way as to avoid any conflict in their objectives The advantage of this approach is that the perspective is system wide Overall system performance can be improved with this However there is one drawback with this approach This approach needs extensive commu nications In case of disruption in communications local controllers will behave in an unpredictable way which may endanger system security

2 3 2   Use of non-conflicting local controls

The second approach is to have only local controllers designed in such a way as to avoid any conflict between them For example one controller may be assigned the task of maintaining a scheduled power flow, another may be assigned the task of maintaining a proper voltage profile still another may be provided a different task for example maintaining a constant power angle

The best approach will be to have a master control with extensive and reliable communications and keeping local control objectives as backup in case of disruption in communications

This thesis discusess such issues related to the parallel operation of two control- lable lines supplying power from one point to another, where one line is a variable series compensated (VSC) AC line and the other is an HVDC line

2 4 Variable series compensation

For variable series compensation of an AC line various schemes have been suggested all of them using power electronics devices Of these the most attractive is a device called TCSC(Thyristor controlled Series Capacitor) It consist of a TCR(Thyristor Controlled Reactor) in parallel with a fixed capacitor It gives continuos control over its impedence through variation of thyristor firing angle
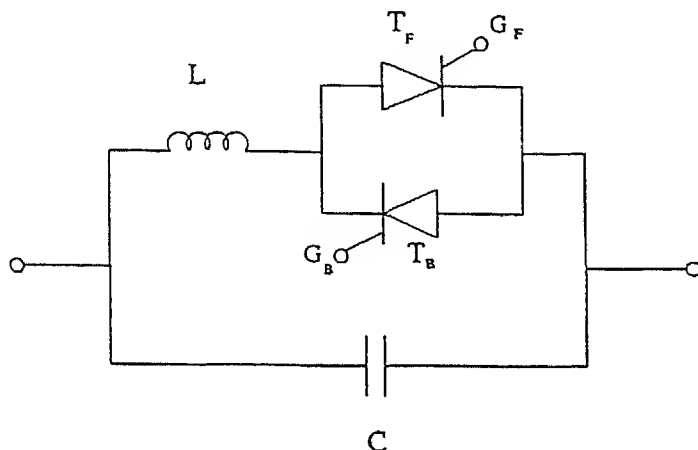
Figure 2 1 TCSC

2 4 1 Impedence characteristics of TCSC

In TCSC, thyristors are fired when the capacitor voltage and currents are opposite in polarity This means firing the forward looking thyristor of the anti parallel pair between 90^0 to 180^0 with respect to zero crossing of capacitor voltage This establishes a loop flow in the parallel TCR fixed capacitor circuit which change the voltage appearing across capacitor This changes the equivalent impedence of the TCSC

TCSC reactance as a function of its firing angle α can be found by taking parallel combination of TCR rectance and fixed capacitor reactance But this does not give the exact value, as shown in [12] If the reactance is calculated in this way the value calculated is less than the actual value and the error increases as α decreases A

10

more realistic estimate is given by the following formula [17]

$$X = \frac{1}{\omega C} \;-\; K_1 \frac{2\sigma + \sin 2\sigma}{\pi \omega C} \;+\; K_2 \, \cos^2\sigma \frac{K \tan K\sigma - \tan\sigma}{\pi \omega C} \qquad (2\ 1)$$

where

$\sigma = \pi/2 - \alpha$

$K = \lambda/\omega,$

$\lambda = 1/\sqrt{(LC)}$

$K_1 = \frac{K^2}{K^2-1},$

$K_2 = \frac{4K^2}{(K^2-1)^2}$ and

α is the firing angle

The Figure 2 2 shows the impedance characteristics of TCSC as a function of firing angle of thyristors The characteristics shown is for L_{TCSC} of 15 mH and C_{TCSC} of 204 83 μF which are the values used for the TCSC taken in the system under study in this thesis In the figure a positive value denotes capacitive reactance and a negative value denotes inductive reeactance As can be seen from the curve, for smaller values of firing angle, TCSC reactance is inductive while for larger values, it is capacitive There exists a point midway through, where the TCSC reactance switches from inductive to capacitive This point is called the resonance point of the TCSC In and around this point, TCSC reactance is very large This large reactance region is known as quasi resonance zone of TCSC [12] TCSC is never operated in this region

2 4 2   Harmonics generated by TCSC

Since TCSC is a switched device, it generates harmonics Only odd harmonics are generated [12] Of the harmonics generated, third harmonic is dominant Its magnitude increases as the magnitude of TCSC impedance increases Because of this, the TCSC reactance is generally restricted to three times the value of fixed capacitor reactance The harmonic content of TCSC voltage is very high It may be as high as 20% But most of the harmonics generated circulate only in the parallel TCR capacitor circuit This is because the value of capacitor reactance is much less compared to reactance of the rest of the network So the amount of harmonics

Figure 2 2   Impedence chracteristics of TCSC

injected in the system is very low   The harmonic content of line current is very low being of the order of 1-2%

Because of the low harmonic content of line current it is a better signal for firing reference [15] This means a firing angle of $180^0 + 0^0$ to $180^0 + \alpha_{res}$ when TCSC is operating in inductive mode and a firing angle of α_{res} to 90^0 when TCSC is operating in capacitive mode where α_{res} is the firing angle at the point where TCSC reactance shifts from inductive to capacitive The only problem with current reference firing is that switching from inductive mode to capacitive mode or vice-versa is problematic since for that the firing circuit not only needs to fire the thyristors at the desired angle, but it needs to find in which mode the TCSC is working But considering that the TCSC is usually operated only in capacitive mode, this problem does not occur under normal mode of operation

2 4 3   Basis for chosing the value of TCSC reactor

The value of reactor used for TCR is very important in TCSC First of all the value chosen should be such that only one resonance point exist Also,The natural freqency of TCSC L C circuit is dependent on it As value of L increases, natural frequency decreases This has a bearing on the response time of TCSC As natural frequency decreases, TCSC response gets sluggish, although the effect is not very pronounced Larger reactance gives advantages which outweigh this disadvantage The first is

12

that it decreases the value of α_{es} thus increasing the control range available in the capacitive mode Also as size of reactor increases loop current decreases for the same value of TCSC equivalent impedance So the thyristors with lower ratings can be used This decreases the cost of TCSC But then with increasing reactor value cost of reactor increases

So a compromise has to be made both in respect of economy and performance Generally, the value of reactor is such that the natural frequency of L-C circuit is between 120 to 150 Hz [15] But this is not a rigid parameter and a higher value of reactor (meaning a lower value of natural frquency) can be used if the control range desired is high[12]

2 4 4   Speed of response of TCSC

As discussed before the speed of response of TCSC is a function of the value of reactor But a greater effect will be that of the operating point of TCSC As the operaing impedance increases TCSC response time increases The TCSC response can be approximated by a fourth order model as given below[17]

$$Z(s) = \frac{\omega^2}{(1 + s\tau)^2(s^2 + 2\omega\zeta s + \omega^2)} \tag{2 2}$$

As firing angle α decreases(ie as impedance increases) τ and ζ increase while ω decreases For the TCSC intalled at Kayenta Arizona[USA], the value of ζ ranges from 0 25 to 0 75, ω ranges from 58 to 18 and value of τ ranges from 0 003 and 0 012 for α varying from 170^0 to 150^0 However TCSC response can be approximately modelled as a first order delay

$$Z(s) = \frac{1}{1 + s\tau} \tag{2 3}$$

The TCSC intalled at Slatt(USA) have been modelled like this in the studies The delay is approximtely 15 ms for it [14]

2 4 5   The control modes of TCSC

TCSC is operated in two control modes, namely vernier and bang-bang In the vernier mode, the value of firing angle can be anything between α_{min} to 180^0 (for

firing synchronised to the capacitor voltage) The value of TCSC can be varied smoothly in this mode and control is continuous

In bang bang mode value of firing angle is either 90^0 (thyristor fully on) or 180^0 (thyristor fully off) (for firing synchronised to the capacitor voltage) Bang-bang operation has been found to be useful in improving transient stability of the system [11]

2 4 6 Firing control for TCSC

As mentioned before current is a better signal for firing reference The TCSC installed in Kayenta(USA) uses this For firing control either IPC(Individual Phase Control) or EPC(Equidistant Phase Control) can be used Being a series connected device, the requirements on firing circuit for TCSC are less stringent compared to shunt connected devices This is because for it the current will never go to zero even in case of severe faults, so the recovery of firing circuit after the fault will be fast

2 5 HVDC link

2 5 1 Basics

An HVDC link is fully controllable in the true sence of the word It can control power anywhere from zero to its maximum capacity It can even reverse the direction of power flow

In an HVDC link, rectifier controls current by controlling the firing angle alpha and inverter controls voltage by controlling extinction angle gamma PI controls are used for both

In the DC link, basic formulas are

$$V_{dr} = V_{dor}cos\alpha_r - R_{cr}I_d \qquad (2\ 4)$$

$$V_{di} = V_{doi}cos\gamma_i - R_{ci}I_d \qquad (2\ 5)$$

$$I_d = (V_{dr} - V_{di})/R_{line} \qquad (2\ 6)$$

where,

V_{dr} and V_{di} are the DC voltages at rectifier and inverter respectively,

I_d is DC line current,

R_{line} is the DC line resistance

R_{cr} and R_{ci} are the commutating reactances at the rectifier and the inverter respectively,

α_r is the firing angle at the rectifier,

γ_i is extinction angle at the inverter

$V_{dor} = 3\sqrt{2}E_{LLr}/\pi$ where E_{LLr} is the line to line voltage at the rectifier bus and

$V_{doi} = 3\sqrt{2}E_{LLi}/\pi$ where E_{LLi} is the line to line voltage at the inverter bus

2 5 2 Voltage Dependent Current Order Limits (VDCOL)

DC link draws reactive power from the AC system at both ends   If the AC side voltage becomes too low and the current order remains same, it may cause voltage collapse in a weak AC system because of the high reactive power demand at low voltages   To prevent it, VDCOL is used to limit current order under low voltage   This also prevents repetitive commutation failure under faults by reducing the current

The complete V I characteristics for the DC link is shown in Figure 2 3   If voltage falls below V_{ul}, VDCOL comes into action   If voltage goes even below V_{ll}, current order is fixed at some minimum value

2 5 3 Power control on the DC link

From the operating point of view, it may be desired to control power on the DC link rather than current   For this a block is needed which convert the power order into current order   The structure for this controller is shown in the Figure 2 4

The dc link should respond fast to changes in Pdc_{order} So the time constant T2 is very small, being of the order of 5 50 ms   However, to avoid instabilty at low short circuit ratios, the time constant T1 should be large, being of the order of 0 1

2 seconds[18]   A minimum limit on measured voltage is kept to avoid very high current order
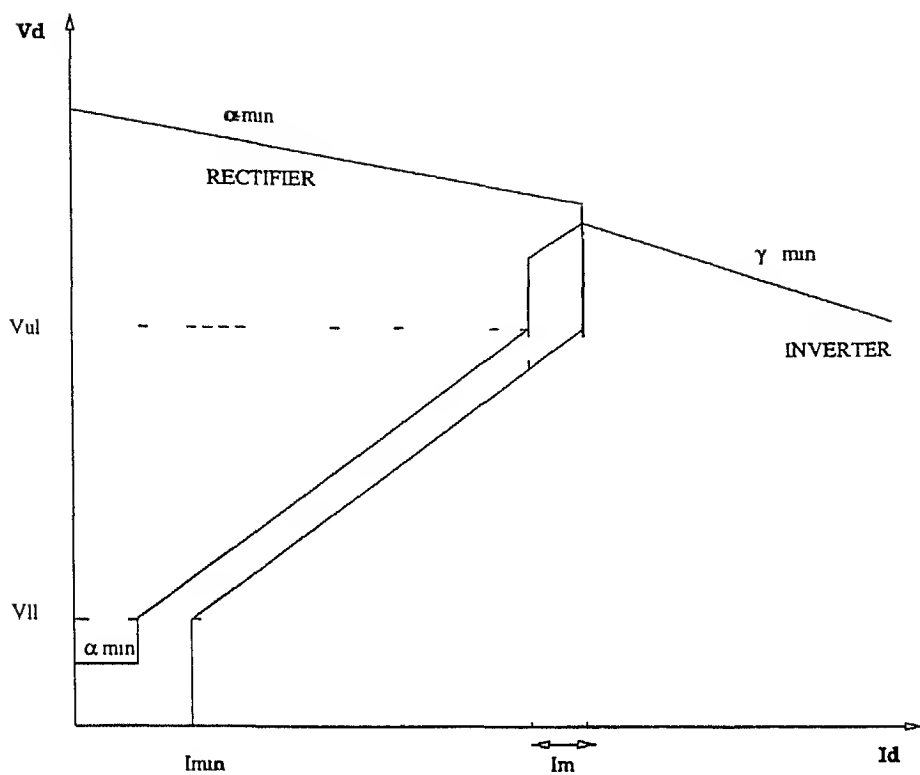
Figure 2 3 V I characteristics for DC link
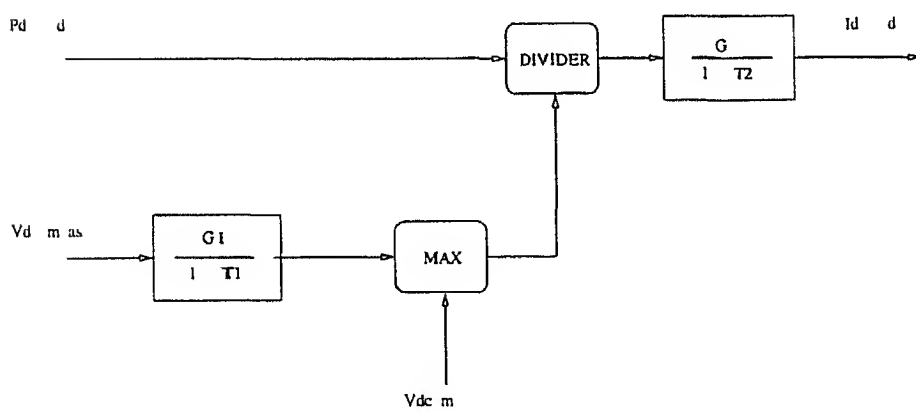
Figure 2 4 Power control for DC link

16

2 6 Control strategies for a variable series compensated AC line operating in parallel with DC line

The general control mode for HVDC link is current/power control In the case taken for study here DC link controls power Since in most of the cases HVDC link will exist prior to the installation of the TCSC on the parallel AC line the control strategy adopted should be such that it does not require modification in the controls of the HVDC link Also it is desirable that the controls used for the TCSC use only locally measurable signals

The control strategies possible for TCSC are discussed below

2 6 1 Reactance control

In this, TCSC operates as a constant reactance This does not use any closed loop control An Xc_{order} is supplied to the control which by using a look up table determines the corresponding firing angle α This method does not come in conflict with HVDC controls But for transients conditions due to faults or set point changes it does not give any advantage since it behaves like a fixed capacitor

XC ORDER → LOOK UP TABLE → FIRING ANGLE

Figure 2 5 Reactance control of TCSC

2 6 2 Power Control

This control strategy utilizes a PI controller to maintain a scheduled power flow over the AC line The control structure is shown in Figure 2 6

Since the DC line is already keeping the power constant this means that the total power flowing over the corridor is being maintained constant by the controller on the both line This power should correspond to the mechanical power input to

17
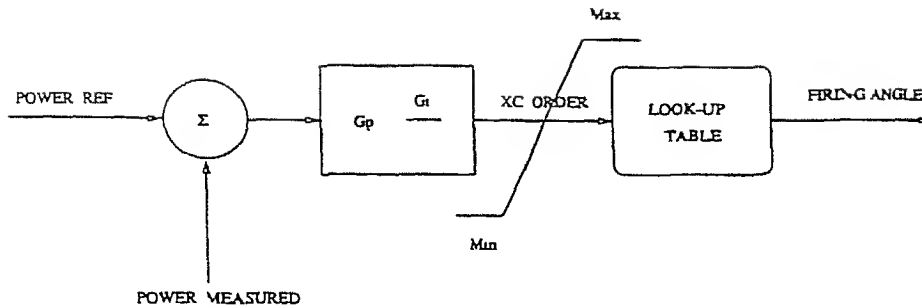
Figure 2 6 Power controller on TCSC

the generator for svstem to have a steadv state operating point Assuming that
svstem is operating in steady state this controller will behave well for faults This
is because in trving to maintain power flow constant on the AC line it indirectlv
helps to keep generator electrical output constant which helps generator to stop
accelerating/decelerating

But faults are not the onlv contigencv a system is likelv to face The control
should be able to deal with all other contigencies like a change in power flow on the
parallel DC line or a change in mechanical input to the generator

A change in the mechanical power input of the generator can occur due to a
number of reasons for example due to outage of a unit in the generating station a
failure of mechanical svstem action of some additional control on the generator like
automatic frequency control etc It mav even be a deliberate decision due to reasons
of economic load dispatch

A change in power flow on the parallel DC link can occur due to abnormal
operation of controls outage of a pole or the VDCOL action in case of low voltages

In case of anv of these contigencies the performance of the power controller will
be unsatisfacorv For example in case of an increase in power flow on the DC line
power on the AC line will start decreasing since the mechanical power input to the
generator is constant Power controller on the AC line will react to this bv increasing
the capacitive reactance of TCSC Now if this increase is verv fast generator mav
go out of synchronism If the action is slow the controller output(X_{corder}) will hit
its maximum limit and will stav there thus losing its control over the line The
latter possibilitv is more likelv to happen since TCSC response is not verv fast

18

Even if the controller changes $\backslash c_{order}$ fast TCSC will take some time to acheive this value

An apparent solution to this problem is to keep a master control to keep the total power over the corridor constant This is shown in Figure 2 7

P_tot I_REF   Σ   P_ac_REF

+

Pdc_measured
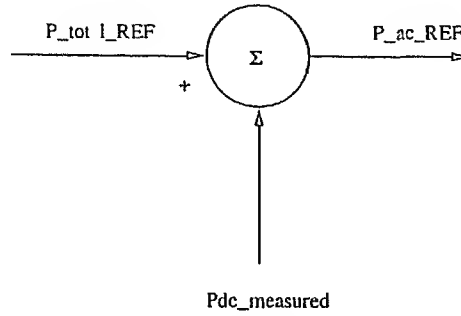
Figure 2 7 Master control

The logic behind this is that this will keep total power over the corridor constant thus matching the mechanical input to the generator even if the power flow on the parallel DC line changes But a DC links behaves as a non linear load on the AC system at both ends A DC link can not be modelled as a series impedance So even if the power over the corridor remains the same the parallel link's equivalent impedance changes This will change the power flow in the other parts of the network Again, this will cause an unbalance in the electrical output and the mechanical input of the generator So assuming that the generator remains stable, the power order of the AC line will be unattainable So the TCSC controller will hit its upper or lower limit The HVDC link will attain its power order, being faster in response compared to TCSC However, if there are alternate parallel paths for power to flow, this control strategy will work

This is verified by the simulations in this thesis

The point to be noted here is that in some very particular cases, the parallel links equivalent impedance may become the same for some particular compensation level In that case power controller may work

Another drawback of this control strategy is that it will not work in case of a change in the mechanical power input of the generator since this control strategy

19

basically tries to keep electrical power output of the generator constant by trying to keep power flow over the corridor constant

So although power control is an attractive proposition in many cases it will not work for the case of of parallel operation of HVDC and variable series compensated AC line To deal with the control problems associated with such a system this thesis proposes regulation of power angle across the parallel AC-DC link through use of TCSC

2 6 3 Delta regulation

The control strategy proposed here maintains a constant power angle delta across the parallel AC DC link by varying TCSC reactance in response to changing network conditions The controller used for this purpose is a simple PI control
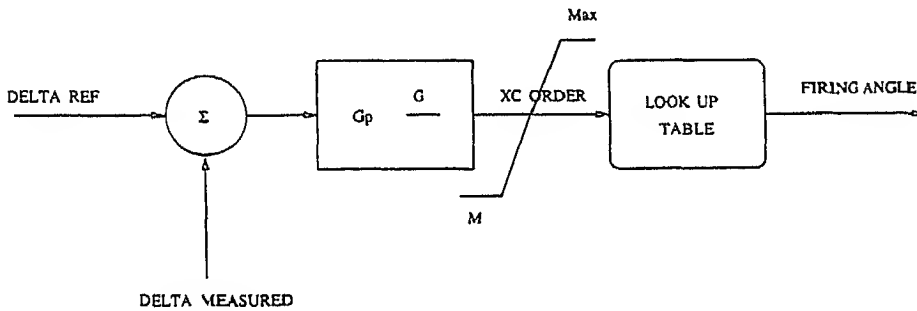
Figure 2 8 Delta regulator

The power angle δ across the AC DC link approximately follows the equation

$$P_{ac} = \frac{V_1 V_2}{X} \sin\delta \qquad (2\ 7)$$

where P_{ac} is power flow over the AC line $V_1\ V_2$ are the terminal voltage at the ends of the line and X is effective line reactance given by

$$X = X_{LINE} - (X_{FC} + X_{TCSC}) \qquad (2\ 8)$$

where X_{LINE} is total line reactance, X_{FC} is the fixed series compensation and X_{TCSC} is the capacitive reactance offered by TCSC It is clear that by changing X_{TCSC} δ can be regulated

20

Delta regulation over the link does not come in conflict with the power controller on the DC line. Given constant mechanical power input of the generator for every value of DC line power flow there exists one steady state value of AC line power whatever be the value of series compensation on the AC line. This controller will adjust the degree of compensation in such a way that the desired value of the power angle δ is obtained at the steady state power level of the AC line. So this controller will work well for the changes in the DC line power flow.

Such an operating point will exist even in the case of mechanical power input change at the generator. Again, the controller will adjust X_{TCSC} to bring δ to the desired value.

In case of large changes in DC power flow or the mechanical input of the generator, the value of X_{TCSC} required to maintain constant δ may be outside the limits of the controller. In such a case the controller output will hit its limit and will stay there.

In addition to avoiding conflict with HVDC controller, regulating delta has the apparent advantage of improving transient stability of the system. The transient instability manifests itself when power angle does not stabilize. Delta regulator will be useful for improving transient stablity since by trying to maintain power angle δ constant, it opposes its movement during transients.

The regulation of δ does not require any explicit co-ordination with DC link controls. So it does not require communications between the two controllers. Also delta across the link can be inferentially measured using locally measurable signals like phase difference across the series compensation. For example, delta across the link is given approximately by

$$\delta_{LINK} = \delta_C \frac{X_C}{X_{LINE} - X_C} \tag{2 9}$$

Here δ_C is the phase difference across the total series compensation (which is locally measurable) and X_C is the value of total series compensation, which is equal to the sum of TCSC reactance and fixed compensation reactance. X_{LINE} is the total line reactance

Chapter 3

System modelling and control design

The system taken here represents an area with large generation supplying power to a large power system The generating area has been represented by a single generator and the receiving area is represented by an infinte bus Embedded in the system is a parallel AC DC link where the AC line is series compensated with TCSC and a fixed capacitor in series At both ends of series compensation the transmission line is compensated by shunt reactors which neutralizes the half line charging of the line This improves the voltage profile of the line [20] The DC link reactive compensation is provided by fixed capacitors and harmonic filters Of the total compensation 40 % is provided by the fixed capacitor and rest is supplied by the harmonic filters

The Figure 3 1 shows a single line diagram of the system

3 1 Modelling of the system

The system is modelled on PSCAD (Power System Computer Aided Design) This package is a graphic user interphase to the EMTDC(Electro-Magnetic Transient DC) program
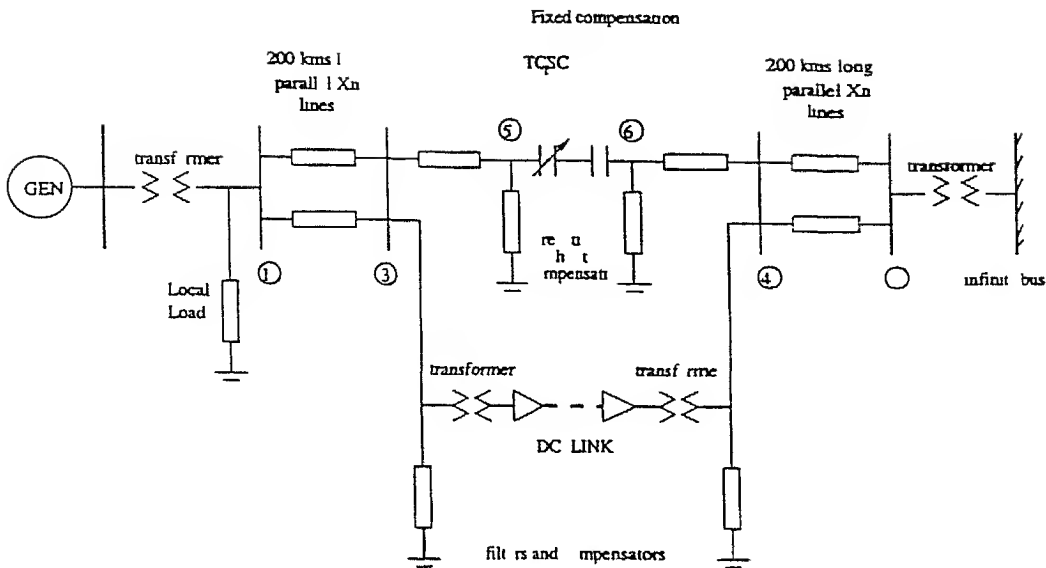
Two half f 800 kms long line

Fixed compensation

200 kms l
parall l Xn
lines

TCSC

200 kms long
parallel Xn
lines

GEN

transf rmer

⑤ ⑥

transformer

① ③

re u
h t
mpensati

④ ◯

infinit bus

Local
Load

transformer

transf rme

DC LINK

filt rs and mpensators

Figure 3 1 System taken for study

3 1 1   Why PSCAD?

The studv done here is interested mainly in fundamental frequencv behaviour of the svstem The question that can be raised than is   what is the need of using PSCAD which does full time domain simulation and is computationally verv intensive?   The fundamental frequencv response of the system can be studied on available stabilitv programs as well which are much less intensive computationallv

Primarilv there are three reasons for using PSCAD

1 No exact model for TCSC is available The fundamental frequencv steadv state impedence of TCSC is given by equation [2 1] But TCSC takes a large time to acheive this steadv state value So in most of the studies done[15] TCSC has been modelled as a first order lag But the EMTP(Electro-Magnetic Transient Program) studies done for TCSC installed in Kaventa shows that the TCSC response is actuallv a fourth order one Further this response not onlv depends on the L-C vales of the TCSC but depends on the rest of the system as well[19] Because of this unpredictable response of TCSC PSCAD is used, which gives exact behaviour of TCSC

23

2. Although the primary concern of this study is the fundamental frequncy behaviour of the system TCSC and the HVDC converters injects harmonics which can interfere adversely with measurement blocks of TCSC controls which can not be ignored Proper filtering may be necessary

   Such interference is found to exist with phase measurement Proper filtering is necesserv for phase measurement which is the feedback signal for the control here

3. The firing circuit will not work properly for the duration of the fault and some time after that due to distortions in zero reference signal Without proper representation of firing circuit any fault study will not give proper results

3 2   Modelling of generator and electrical circuit

3 2 1   Generator

Generator is modelled by the machine model *SNC375* of PSCAD It is a seventh order model of the generator with three stator winding one field winding and two damper windings one each on d and q axis Saturation is neglected

3 2 2   Exciter

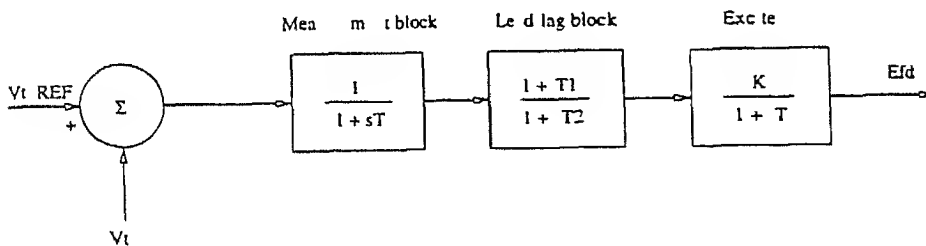Exciter is modelled by exciter model *exci5* of PSCAD the block diagram for which is given in Figure 3 2

Figure 3 2 Exciter block diagram

24

3 2 3   Power system stabilizer(PSS)

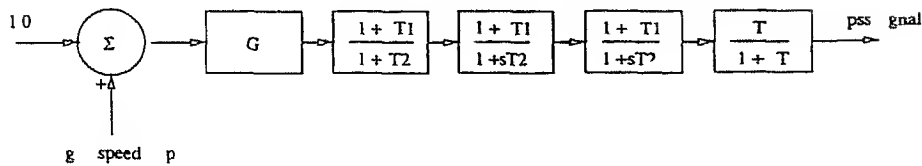PSS has been modelled as shown in the following block diagram

Figure 3 3 PSS block diagram

The mechanical system is not modelled and generator is supplied with fixed mechanical input which is acceptable for stability studies

3 2 4   Transmission line modelling

AC Transmission line is modelled by its pi equivalent   DC Transmission line is modelled by its T equivalent

3 2 5   Load

Load is modelled as fixed impedance

3 2 6   Transformer

Transformers are modelled with both windings and their magnetising currents   No load losses and saturation are neglected

3 2 7   DC Converters

DC converters are modelled by valve group *G6P200* of PSCAD   It models the converter fully with its thyristors and snubber circuits

3 2 8   TCSC

TCSC is modelled with thyristors Thyristor used has inbuilt snubber circuit

3 3   Modelling of HVDC and TCSC controls

3 3 1   HVDC controls

Current controls   This is modelled by the generic current control block *POLPI5*
of PSCAD It is there at both rectifier and inverter It models current margin and
slope of current error characteristics as well at the inverter end   Its block diagram
is given in Figure 3 4

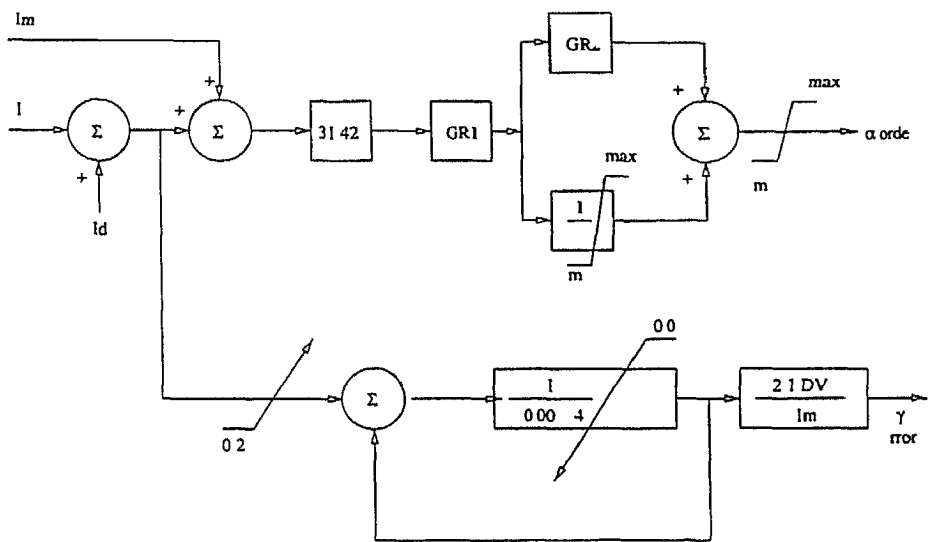

Figure 3 4 Current control

Gamma control   It is modelled by the generic gamma control block *VG6P18* of
PSCAD Its simplified block diagram is given in Figure 3 5

VDCOL   This is modelled by voltage dependent current limit block available is
PSCAD Block diagram for this is shown in Figure 3 6

Complete Vd Id characteristics of HVDC link with VDCOL is shown in Figure
3 7

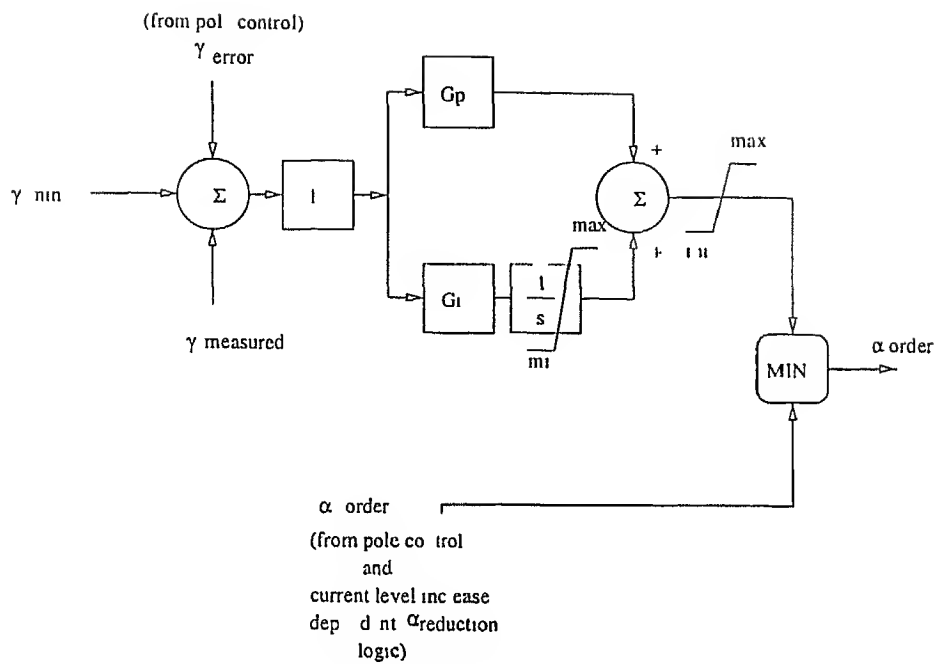Figure 3 5   Gamma control

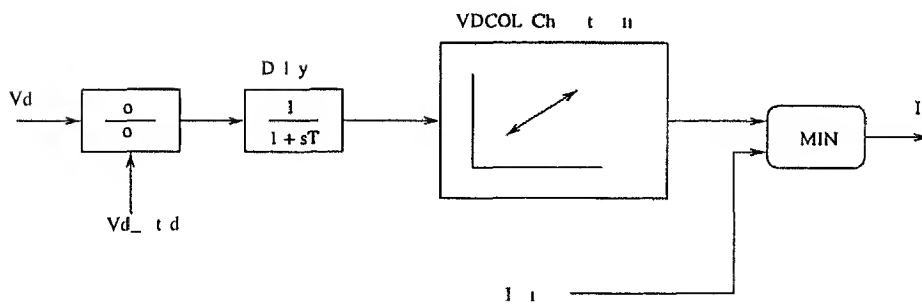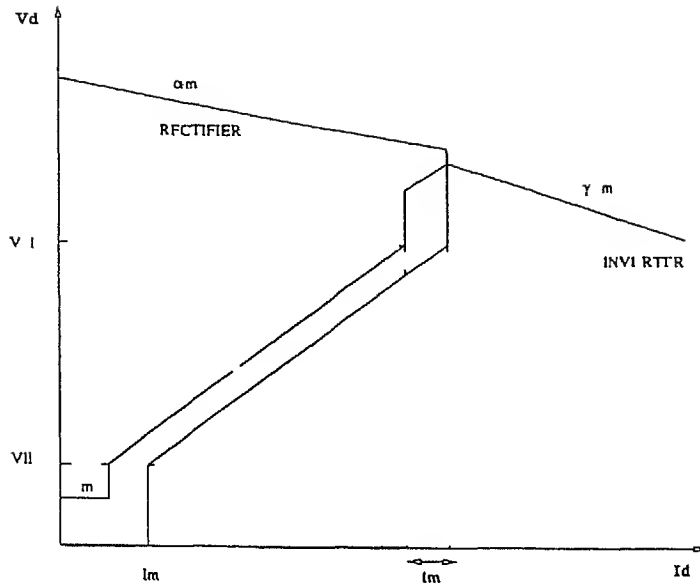Figure 3 6   VDCOL block diagram

Figure 3 7 VDCOL characteristics

3 3 2 TCSC controls

Firing control of TCSC The firing of TCSC is synchronised with line current
The firing scheme used is IPC (individual phase control) The block diagram for
firing circuit is shown in Figure 3 8 The part shown is for the firing of forward
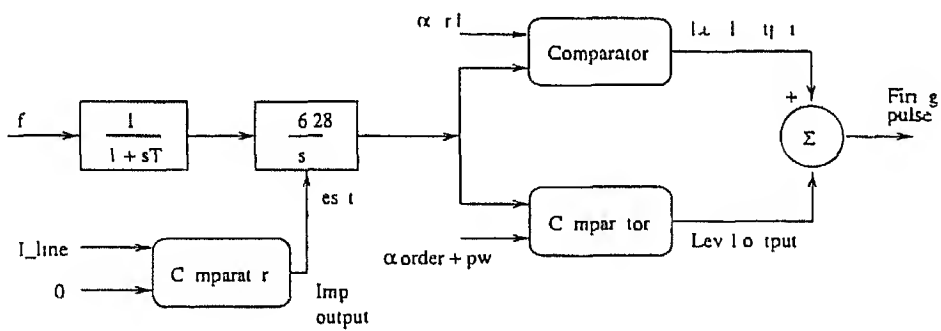looking thyristor of one phase

Figure 3 8 Firing cuircuit of TCSC

In the figure, f is the measured frequency and pw is the pulse width which is
kept 20^0 here

28

Main control of TCSC   The main control of TCSC maintains the angle delta across the parallel AC DC link at a constant value   It uses a PI control   Its block diagram is shown is Figure 3 9
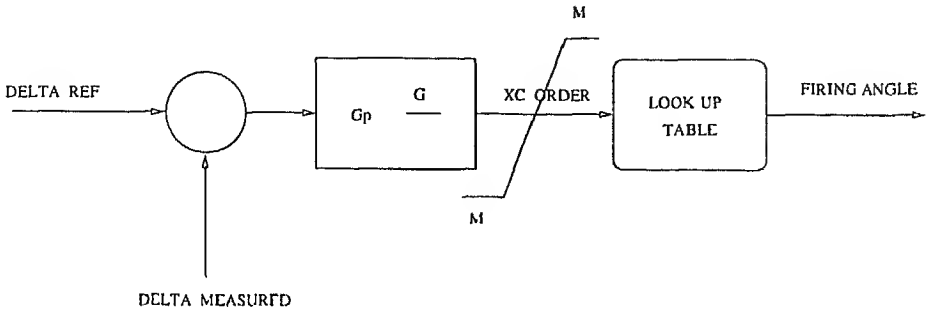

Figure 3 9   Main control of TCSC

A look up table is used to convert the λc_{order} to the corresponding firing angle α There is no absolute necessity for a look up table and the controller output can be directly firing angle α as well instead of Xc_{order} (For this the sign of δ_{REF} and δ needs to be reversed, since the relation between α and λc is inverse)   But since the relationship between α and Yc is highly non linear, specially as Yc increases, the nature of control action will be highly dependent on the operating point without the use of a look up table and satisfactory control action may not be obtained   That is why the look up table approach has been used here

3 4   Choice of control parameters

3 4 1   HVDC controls

PSCAD manual suggests a particular range of values for the values of control parameters of current and gamma control   For current control the suggested range of values are 3 0   6 0 deg/amp sec for integral gain(G_{R1} in fig 3 4) and 0 01   0 02 p u for proportional gain(G_{R2} in fig 3 4)   For gamma control the suggested range of values are 10 0   20 0 sec^{-1} for integral gain(G_I in fig 3 5) and 0 1   2 0 p u for proportional gain(G_P in fig 3 5)   The other two parameters in gamma control are incremental current level C_r (the level which if exceeded by incremental change in

29

I_{dc} will cause $\gamma_{m\,n}$ to increase) and current fade out time constant (for measuring change in DC current) Suggested range of values for these are 0 1 - 0 7 p u and 0 01 - 0 05 seconds respectively

With the simulation following values gave the satisfactory results

1 G_{R1} - 3 0 deg/amp sec

2 G_{R2} - 0 01 p u

3 G_I - 10 0 sec^{-1}

4 G_P - 0 1 p u

5 C_F - 0 4 p u

6 T_F 0 02 sec

Apart from these values other control parameters taken are 0 2618 radians (15^0) for γ_{min} , 0 1 p u for current margin and 0 1 p u for the slope of current error characteristics

3 4 2   TCSC controls

Suitable values of TCSC control parameters (integral and proportional gain) are found by *multiple run* facility of PSCAD Through this the value of a specified quantity can be minimised with the variation of a maximum of two parameters For designing TCSC control the value of RMS error of the controller is minimised with variation of integral and proportional gain of the controller

The optimum values found are as follows

- $G_i = 30\,0$ $G_p = 5\,0$ for $+2^0$ step change in δ_{REF}

- $G_i = 100\,0$, $G_p = 10\,0$ for -2^0 step change in δ_{REF}

- $G_i = 80\,0$, $G_p = 5\,0$ for -100 MW step change in Pdc_{REF}

- $G_i = 45\,0$ $G_p = 2\,5$ for $+100$ MW step change in Pdc_{REF}

Based on these the values chosen are 50 0 for the integral gain and 5 0 for the proportional gain These values give satisfactory performance for the complete range of operating points These values are actual values not the per unit values

3 5 Filtering requirements for TCSC controls

3 5 1 Firing control

The firing control uses line current as the reference signal for firing As the harmonic content of line current is very low (of the order of about 1%) no filters are used in the firing circuit

3 5 2 Measurements

For this control strategy used here, the phase difference δ across the parallel AC-DC link needs to be measured either directly or inferentially The value of measured δ is found to contain a continuous chattering due to presence of harmonics in the system due to both HVDC and TCSC The controls react to this chattering which is undesired So a second order bandpass filter tuned to 50 Hz is connected in the voltage measurement circuit before these voltages are passed on to the phase measurement device At the output of the delta measurement device an averaging device with a time constant of 0 02 seconds is placed to eliminate any remaining chattering The filtering arrangement is shown in Figure 3 10

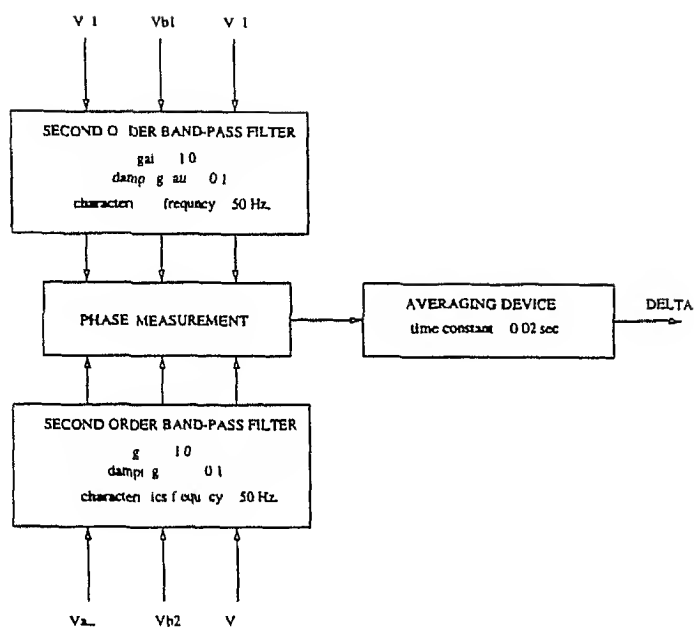Figure 3 10 Filtering arrangements for delta measurement

Chapter 4

Simulation Studies

In Chapter 2 the control strategies for the variable series compensated line operating in parallel with HVDC link have been discussed The TCSC controller based on the strategy proposed is designed in Chapter 3 Here to quantitatively investigate the performance of the controller the system is subjected to a wide range of disturbances (e g faults and reference value changes of the controllers) and system performance is studied

4 1   Non-applicability of power control   simulation studies

Before evaluating the performance of the control strategy suggested here the points made in Chapter 2 about the non applicablity of other control strategies is shown through simulations These control strategies are

1 Both AC and DC lines with individual unco-ordinated power control

2 Both AC and DC lines with co ordinated power controls where a master controller assigns the power references to the individual controllers in such a way that the total power flowing over the corridor is constant

4 1 1 Unco-ordinated power controllers on both lines

In the steady state both lines are maintaining power at their reference value At t = 1 sec, a 100 MW step increase is given to DC power reference The DC link being much faster in response compared to TCSC acheives this power level in a relatively shorter time But the total mechanical power input to the generator is constant so a corresponding decrease occurs in the AC line The power controller of the TCSC tries to bring the power back to its earlier level by increasing V_{crd} , and in the process ultimately hits its upper limit

The response is shown in Figure 4 1 The x axis represents time in seconds
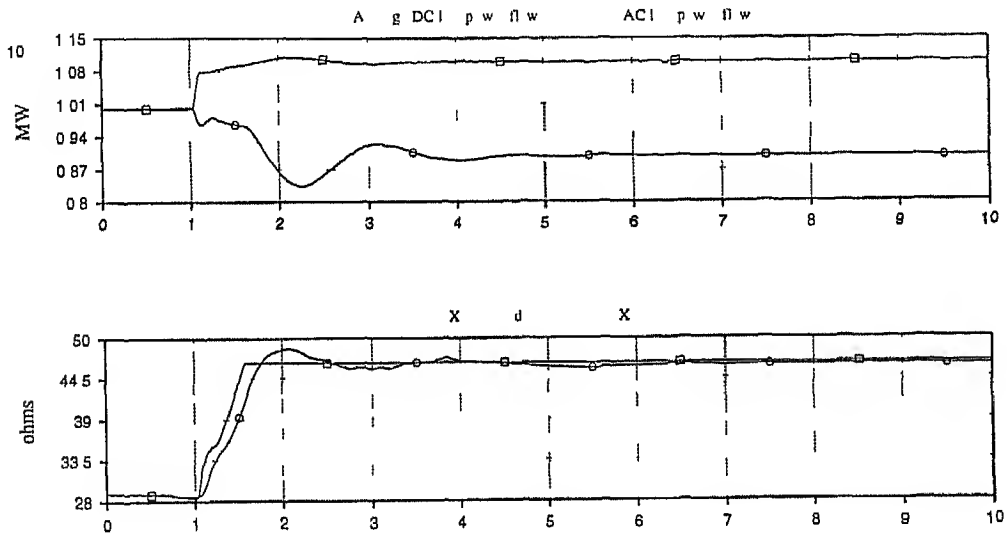
Figure 4 1 System response with both lines trying to control power without co ordination

4 1 2 Co-ordinated power controllers on both lines

As discusses in Chapter 2, this approach also does not work At t=1 sec, DC power reference is changed from 1000 MW to 900 MW Correspondingly, master control decides the power reference for the TCSC power control to 1100 MW But this operating point is not possible As shown in the Figure 4 2, AC line power flow is always slightly less than 1100 MW The power controller reacts to this by increasing

34

$X_{C_{order}}$ of the TCSC ultimately hitting its upper limit In the figure the x-axis
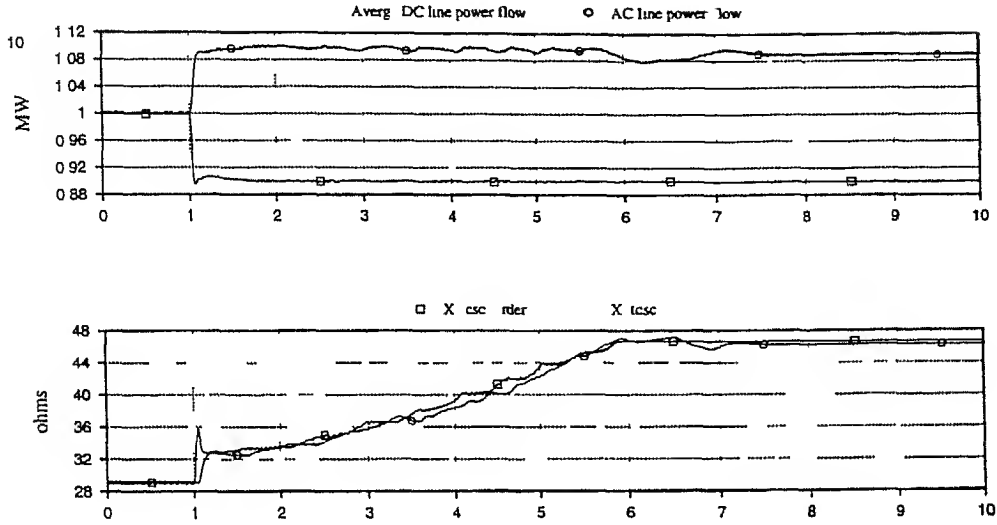

Figure 4 2 System response with both lines trying to control power with co-ordination

represents time in seconds

4 2 Simulations with the proposed control strategy

The control strategy proposed in this thesis uses TCSC as delta regulator ie it keeps the phase angle delta across the parallel AC DC link constant at a given value Exhaustive simulations are done here to evaluate the performance of the delta regulator

The system response is seen for the following diturbances

- three phase solid fault at the generator bus

- three phase solid fault at the transformer before infinite bus

- three phase solid fault at the inverter bus

- three phase solid fault at the rectifier bus

- single line to ground fault at the inverter bus

- single line to ground fault at the rectifier bus

- dc line fault

- three phase solid faults at the both ends of TCSC

- local load rejection at the generating area

- step changes in Pdc_{REF} of the DC link power controller

- step changes in δ_{REF} of the delta regulator

- step changes in mechanical power input of the generator

For important cases the system response is compared with the response of the system with only fixed series compensation

NOTE *For the simulations done here the following convention has been used*

- *The x axis represents time in seconds for all the curves*

- *The disturbances are initiated at t = 1 seconds unless otherwise stated*

- *Fault duration is 5 cycles for all the cases*

4 3   Three phase solid fault at the generator bus

The response of the system with delta regulator for this fault is given in Figure 4 3 As seen from the curves, the delta reach a maximum value of around 50^0 and then settles back to its reference value System response is well damped The system response without the delta regulator is shown in Figure 4 4 Here delta reaches a maximum value of 60^0 So the delta regulator improves the transient stability margin for the system But as can be seen response is somewhat less damped with delta regulator compared to the case of fixed series compensation
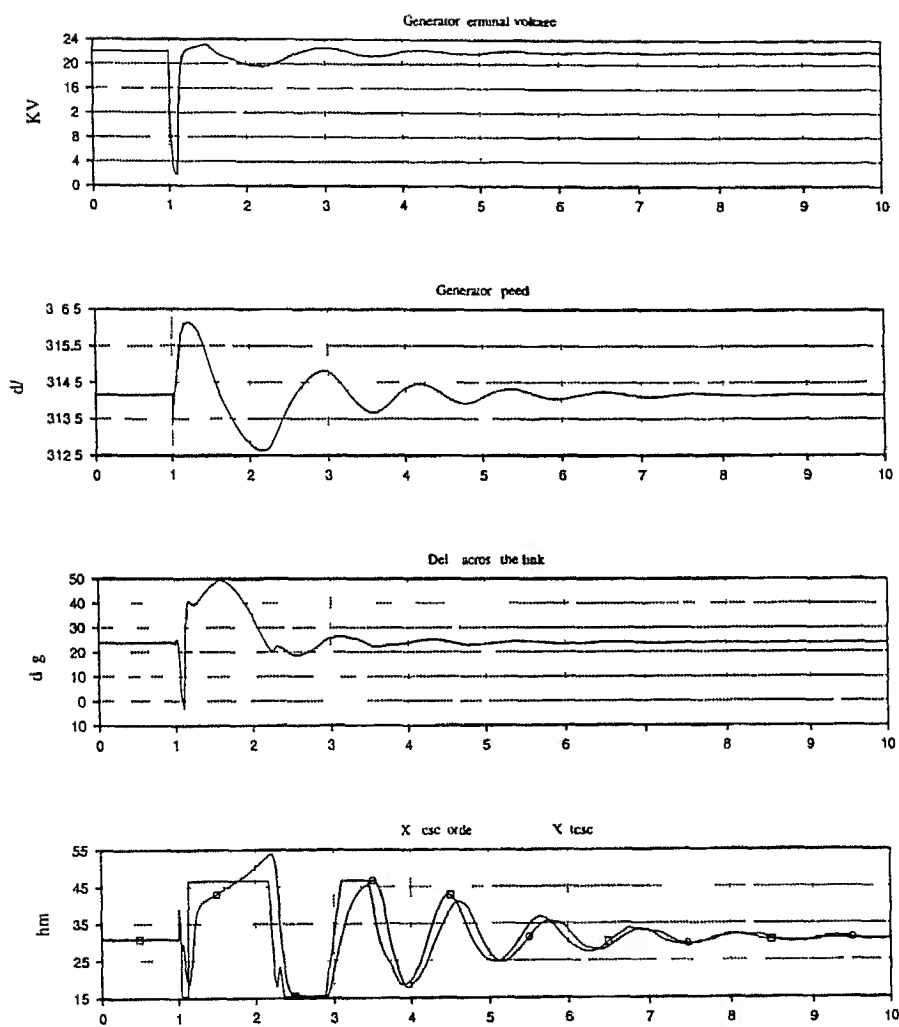
36

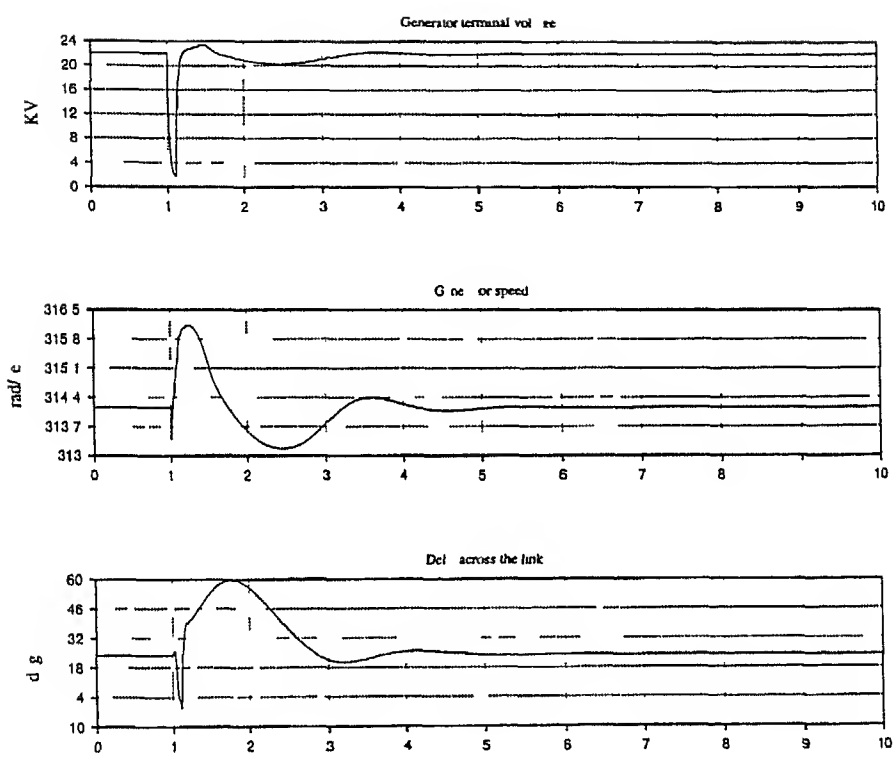Figure 4 3 System response with TCSC delta regulator for 3 phase solid fault at generator bus

37

Figure 4 4   System response with fixed series compensation for 3 phase solid fault at generator bus

4 4 Three phase solid fault at the transformer before infinite bus

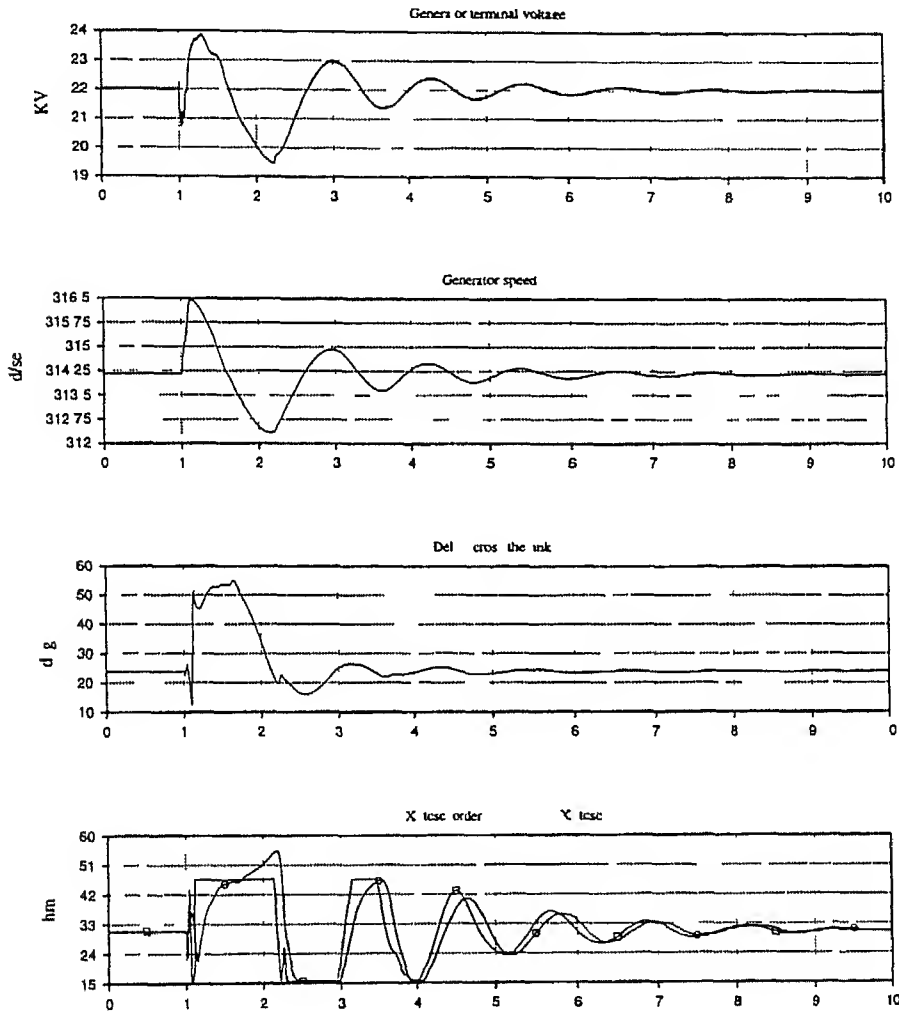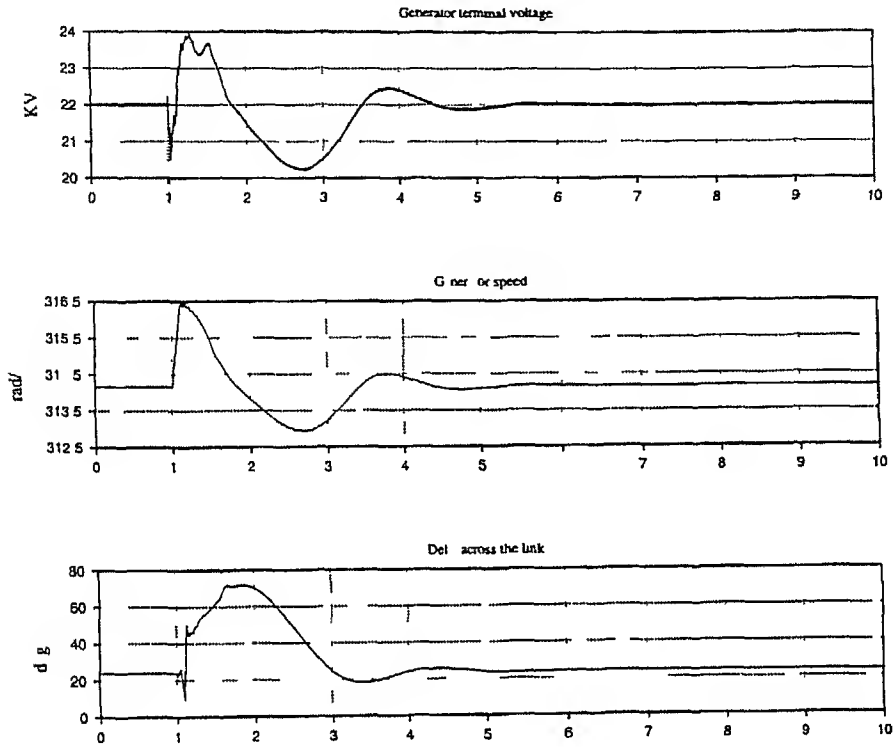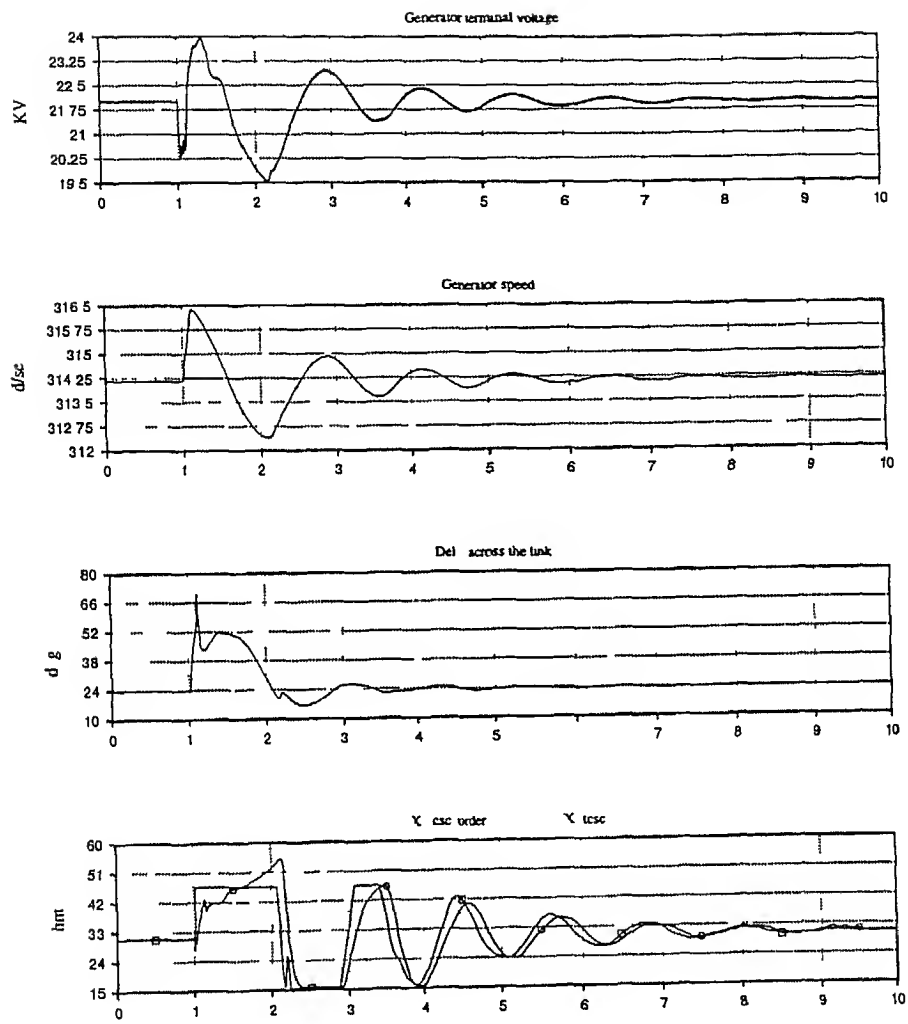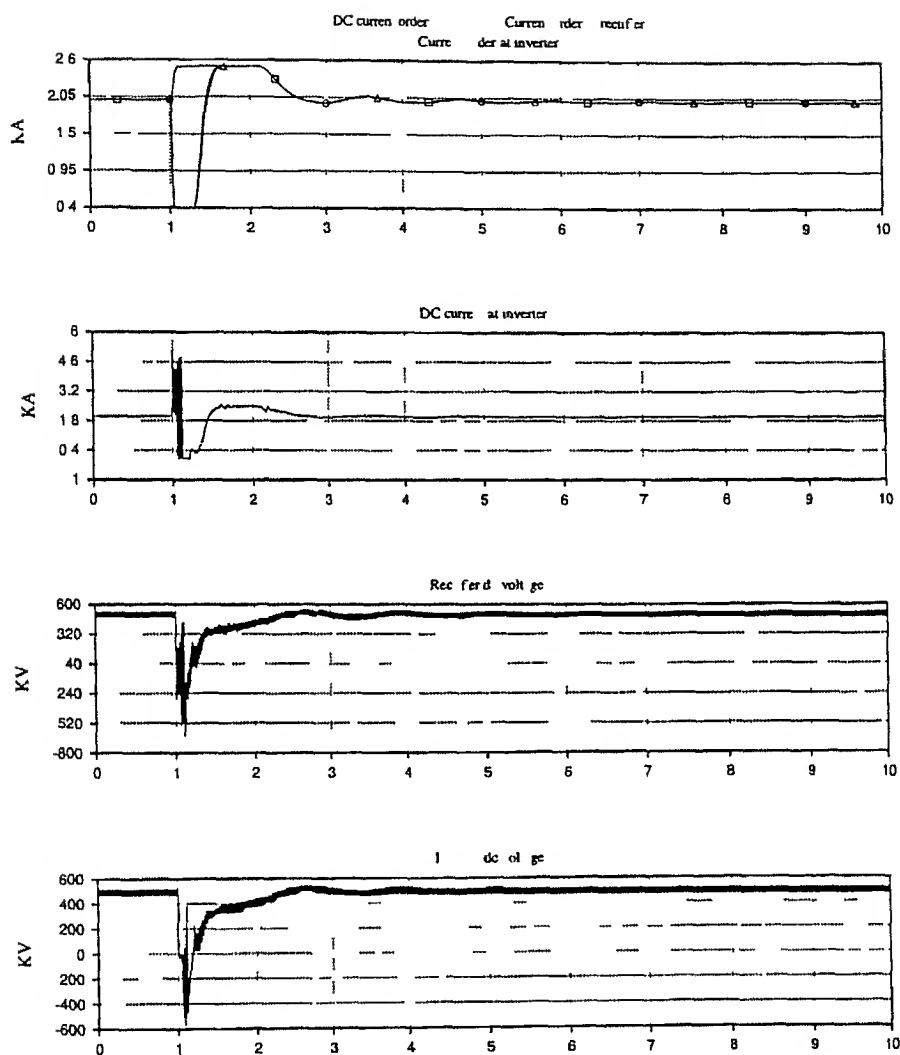The response of the system with delta regulator for this fault is given in Figure 4 5

Figure 4 5 System response with TCSC delta regulator for 3 phase solid fault at the transformer before infinite bus

For this case, the delta reach a maximum value of around 54^0 and then come down fastly After some oscillations, it than settles at its reference value System response

is well damped The system response with just fixed capacitive compensation is shown in Figure 4 6 Here the delta reaches a maximum value of around 72^0 and returns to its reference value after more time lag

Figure 4 6   System response with fixed series compensation for 3-phase solid fault at the transformer before infinite bus

4 5   Three phase solid fault at the inverter bus

The response of the system with delta regulator for this fault is shown in Figures 4 7 4 9   Compared to the system with fixed series compensation (Figures 4 10 4 11) stability margin improves by as much as 20^0

Figure 4 7 System response with TCSC delta regulator for 3 phase solid fault at inverter bus   I

41

Figure 4 8 System response with TCSC delta regulator for 3-phase solid fault at inverter bus   II
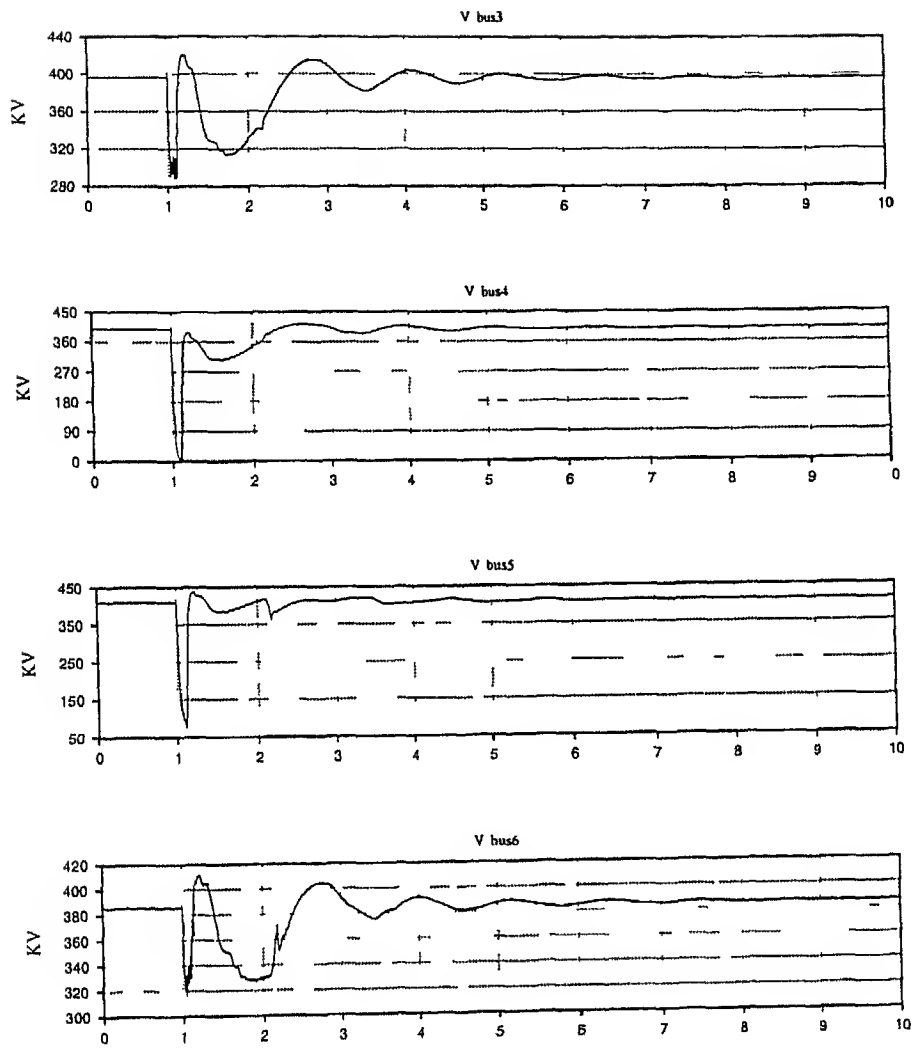
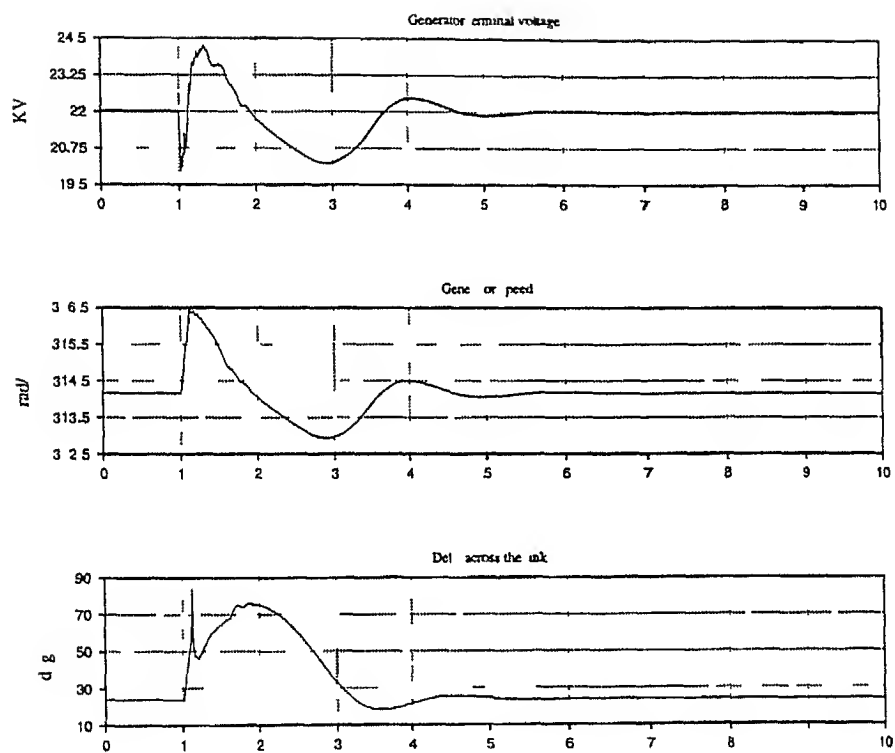Figure 4 9 System response with TCSC delta regulator for 3 phase solid fault at inverter bus III

43

Figure 4 10 System response with fixed series compensation for 3-phase solid fault at inverter bus
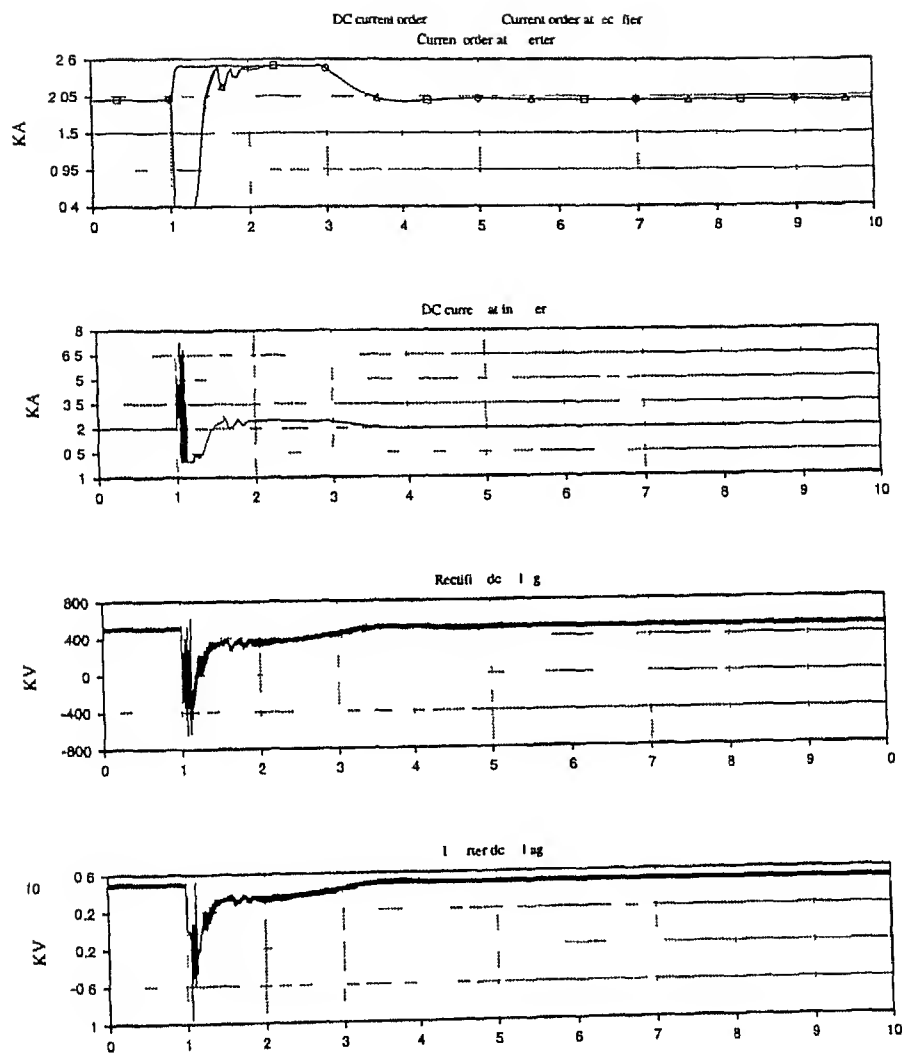I

Figure 4 11   System response with fixed series compensation for 3 phase solid fault at inverter bus
II

45

4 6   Three phase solid fault at the rectifier bus

The response of the system with delta regulator for this fault is given in Figures 4 12-4 14   For the same fault the system loses stability in case of fixed series
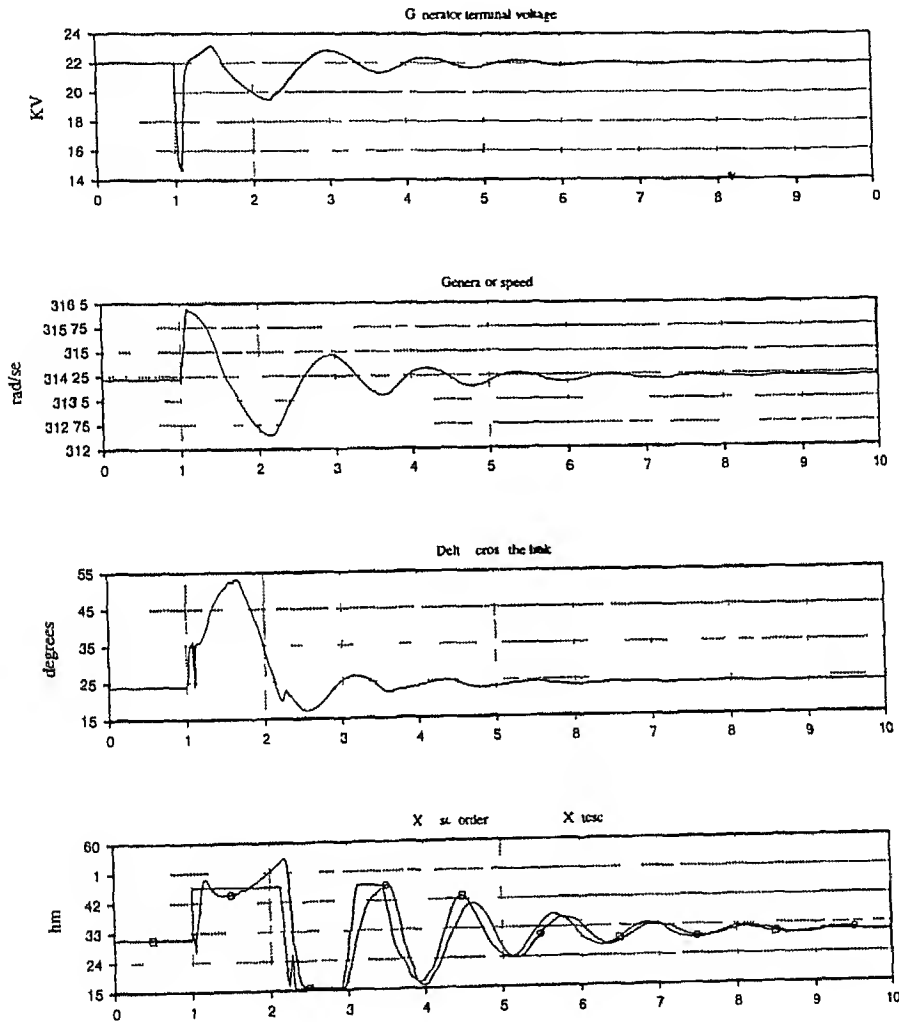

Figure 4 12 System response with TCSC delta regulator for 3 phase solid fault at rectifier bus   I

compensation (Figures 4 15 4 16) while the delta regulator limits the maximum excursion of delta to around 54^0

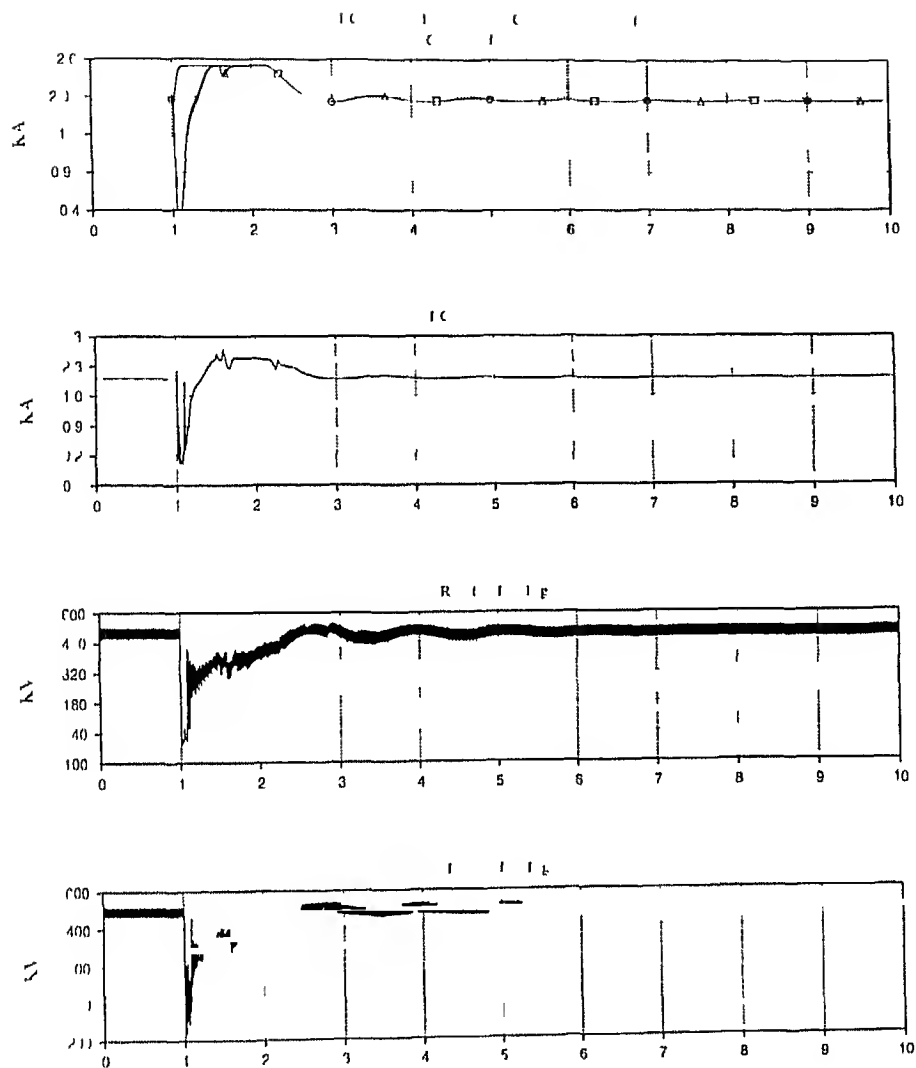Figure 4 13 System response with ICSC delta regulator for 3 phase solid fault at rectifier bus II
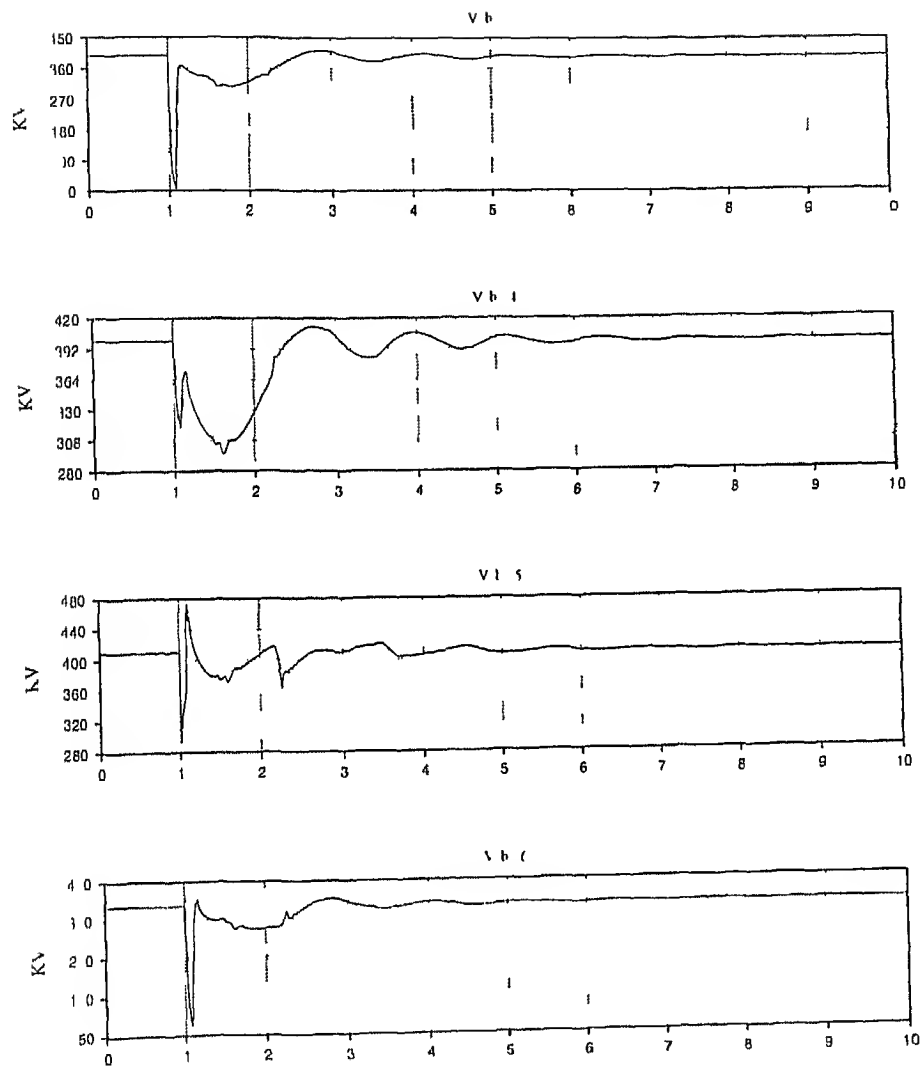
17

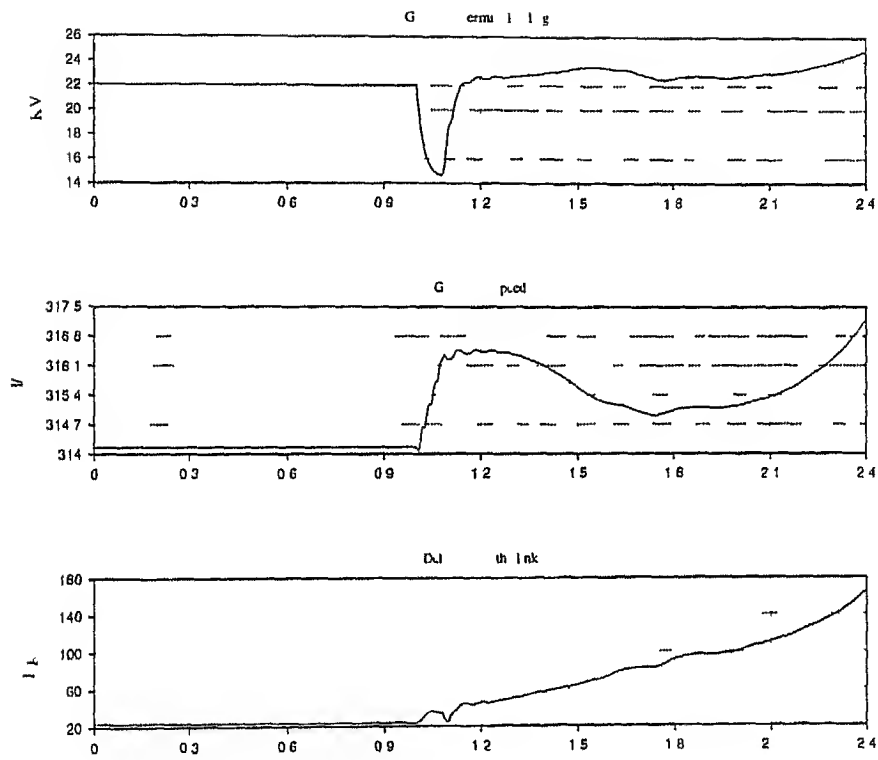Figure 1.11 System response with TCSC delta regulator for 3 phase solid fault at rectifier bus III

48

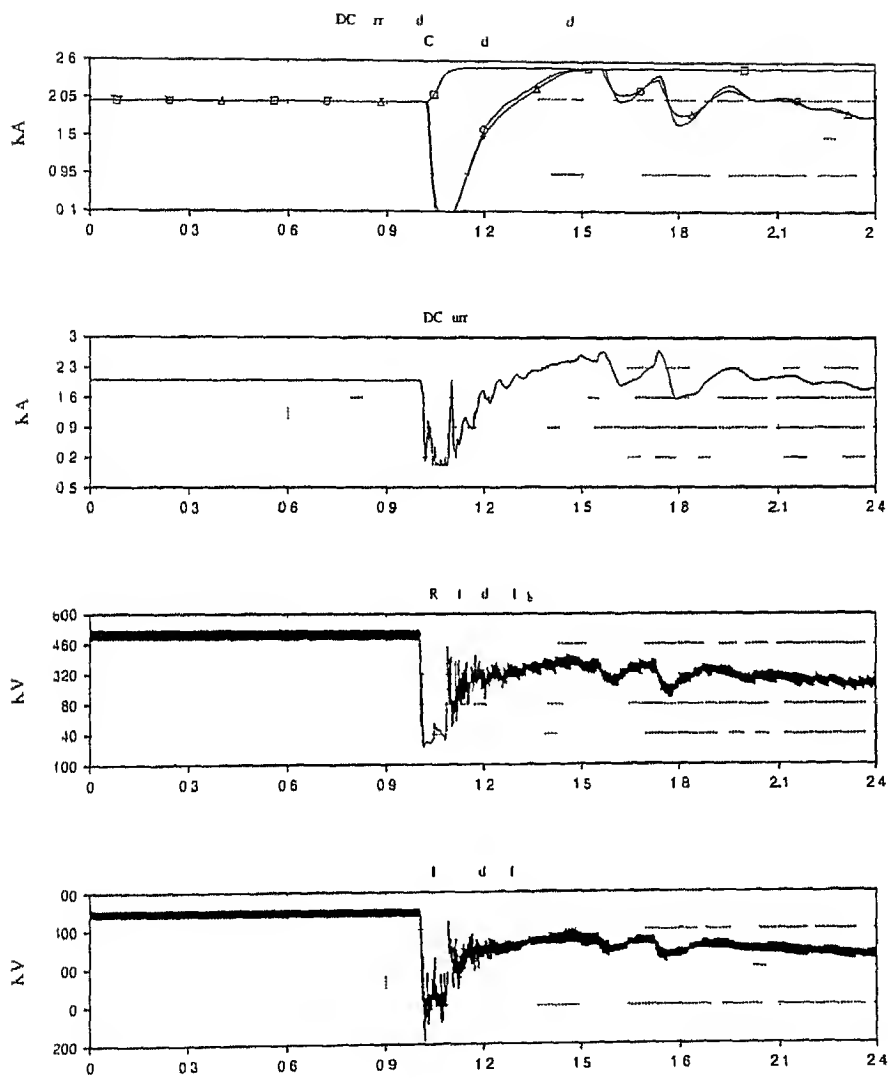Figure 11) System response with fixed series compensation for 3 phase solid fault at rectifier bus I

49

Figure 4 16 System response with fixed series compensation for 3 phase solid fault at rectifier bus II

4 7   Single line to ground fault at the inverter bus

The response of the system with delta regulator for this fault is given in Figures
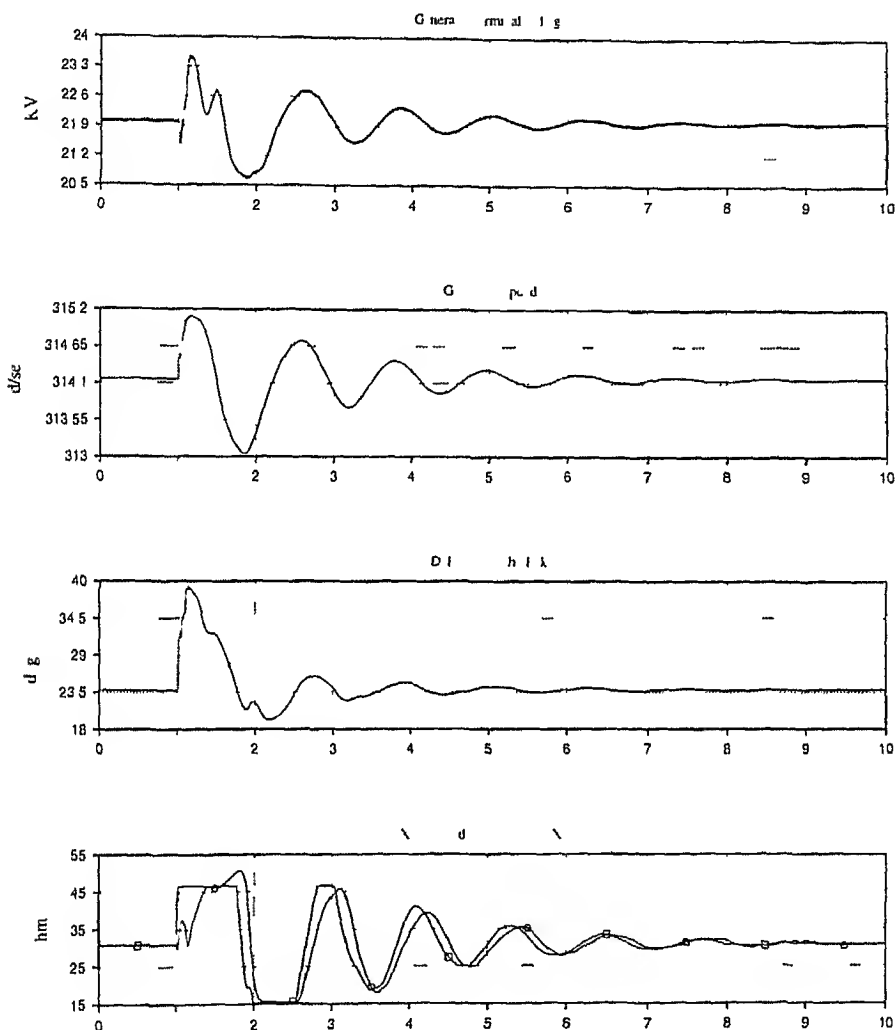4 17 4 18   As far as the maximum excursion of delta is concerned response with

Figure 4 17 System response with TCSC delta regulator for single line to ground fault at inverter
bus I

delta regulator is not much different from that for fixed series compensation (Figures
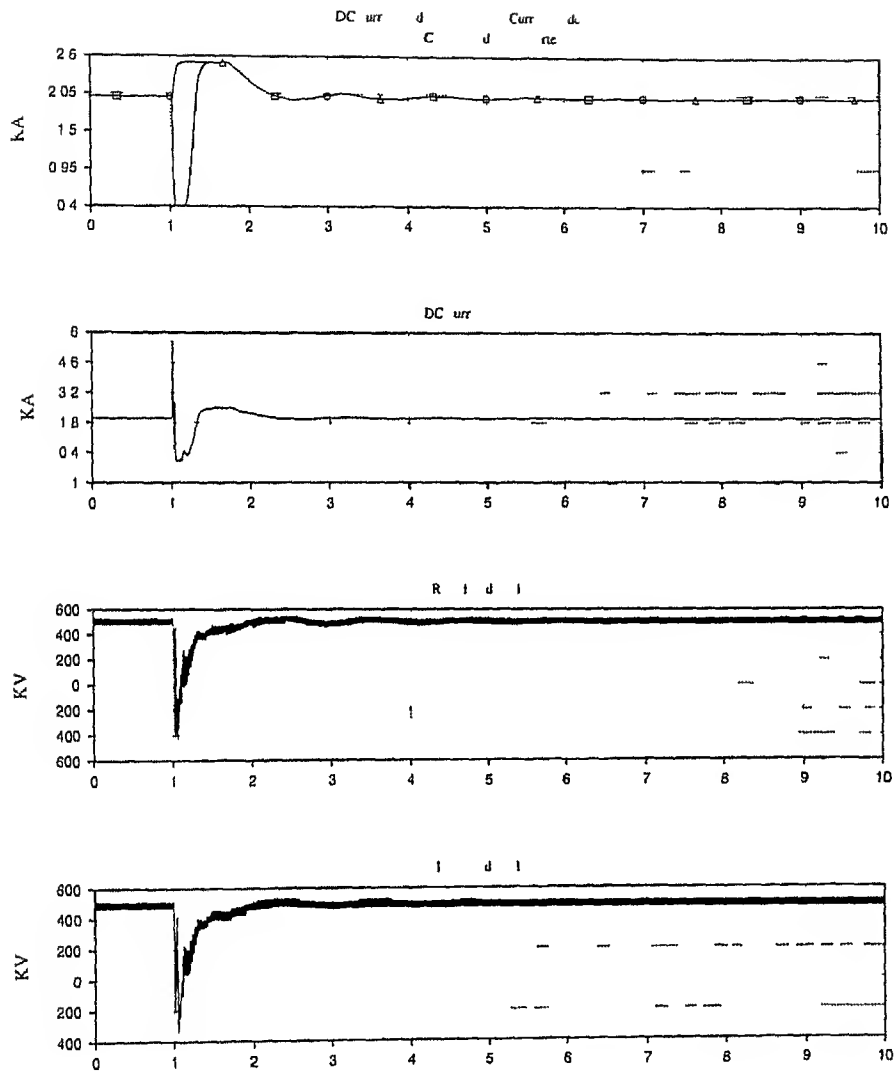4 19 4 20) But with delta regulator, the value of delta comes down faster

Figure 4 18   System response with TCSC delta regulator for single line to ground fault at inverter bus II
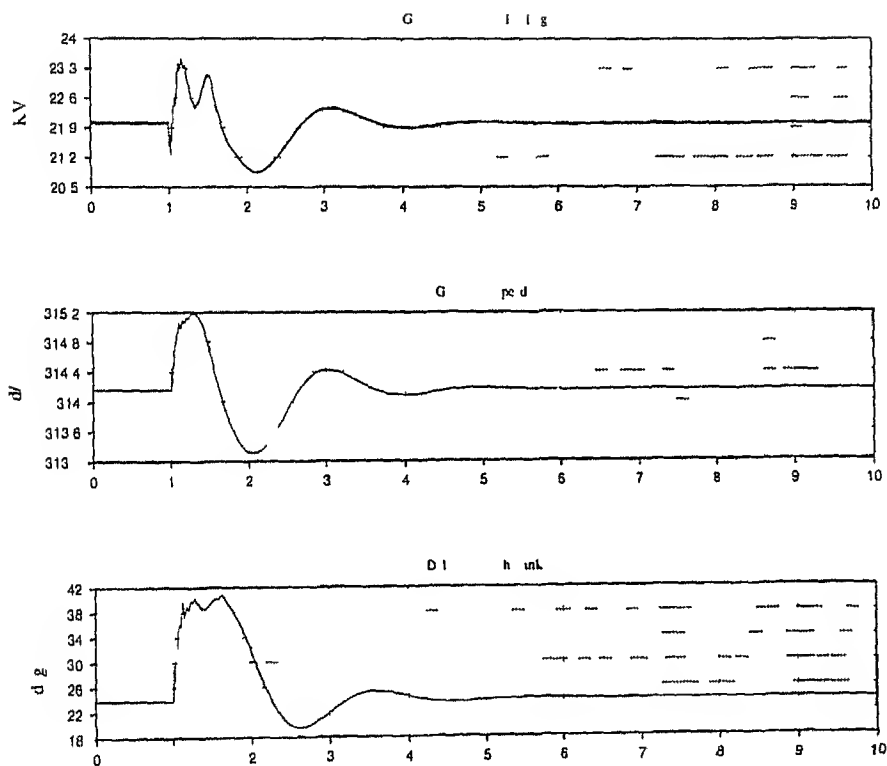
Figure 4 19 System response with fixed series compensation for single line to ground fault at inverter bus I
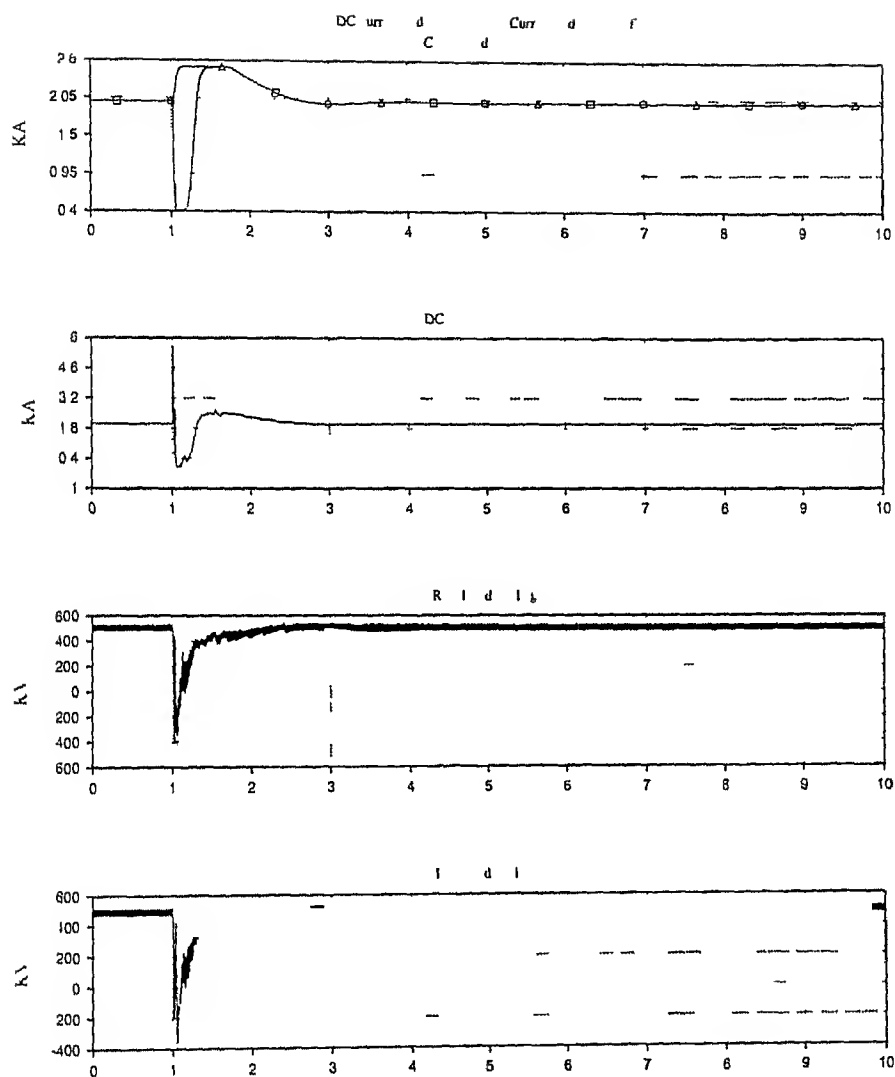
Figure 4 20   System response with fixed series compensation for single line to ground fault at inverter bus   II

4 8 Single line to ground fault at the rectifier bus

The response of the system with delta regulator for this fault is given in Figures 4 21 4 22   For this fault there is no improvement over the case of fixed series
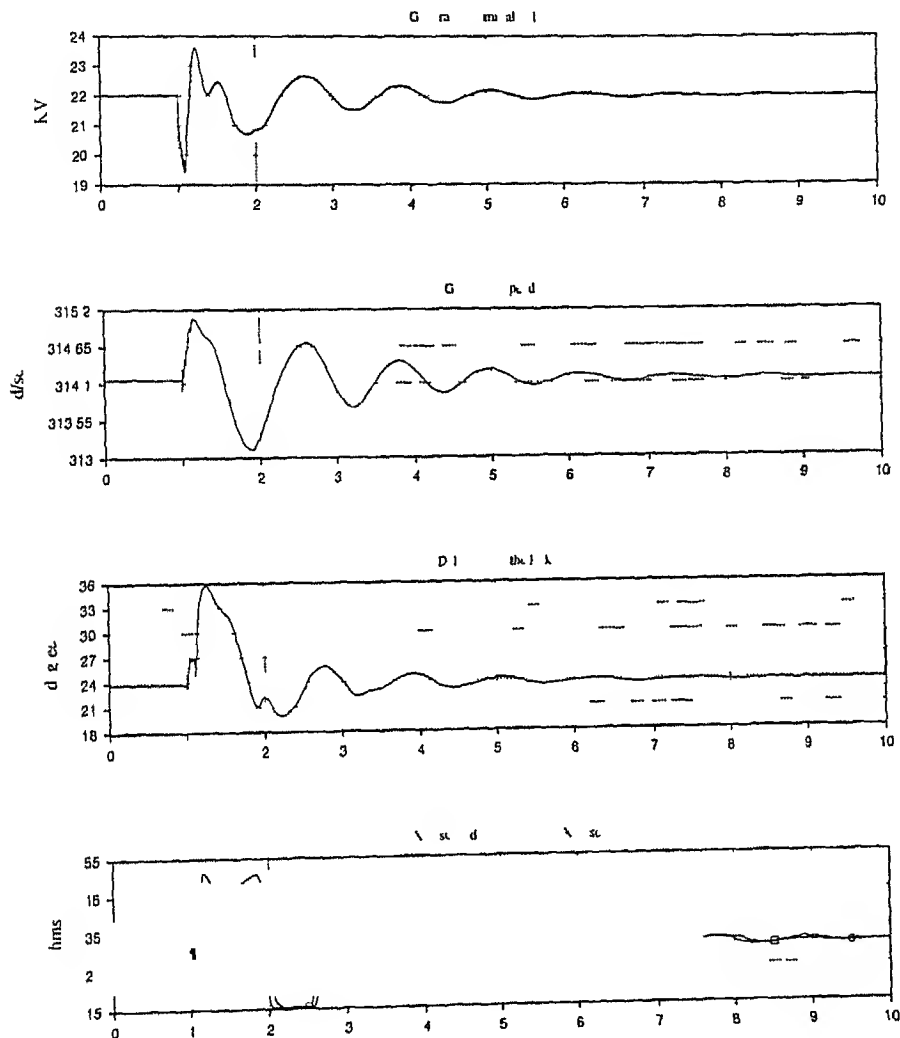

Figure 4 21 System response with TCSC delta regulator for single line to ground fault at rectifier bus I

compensation   The value of delta excursion is somewhat more with the delta regulator, although delta value returns faster to its reference value

The control strategy used here basically assumes balanced conditions, since the

feedback angle delta is the average value of individual angles for the three phases But it is to be noted that the control works satisfactorily even for the unbalanced cases giving a slight improvement compared to the case of fixed series compensation (Figures 4 23 4 24)
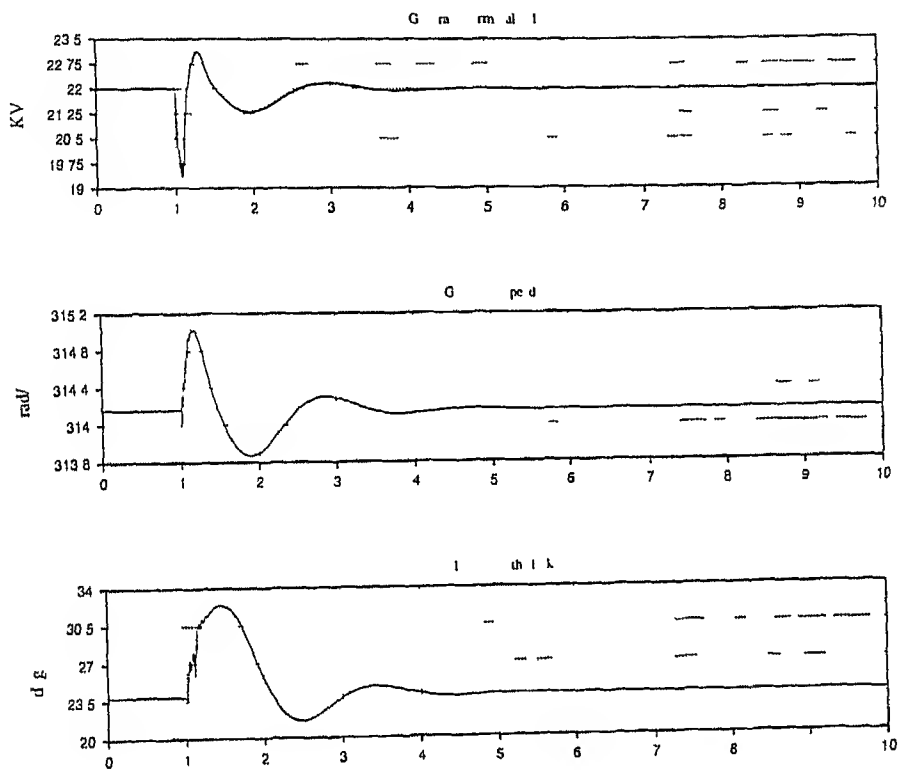

Figure 4 23 System response with fixed series compensation for single line to ground fault at rectifier bus I
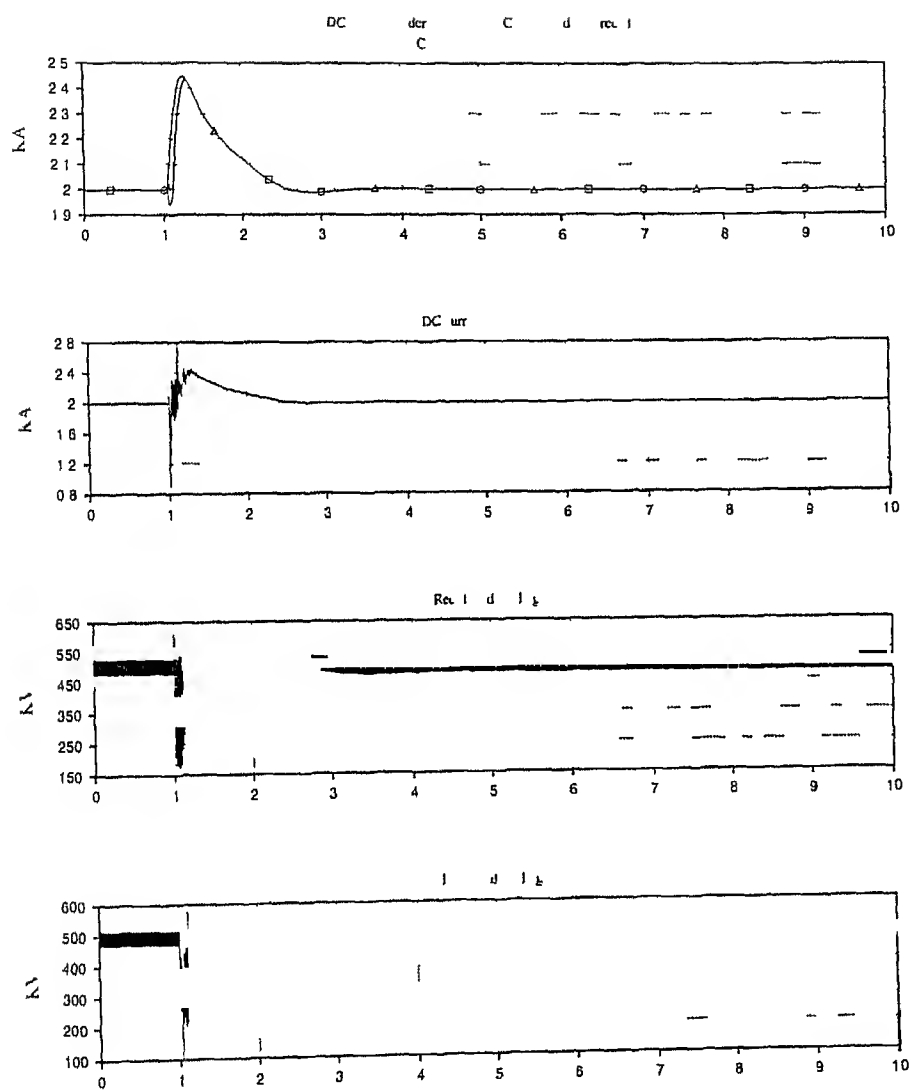
Figure 4 24 System response with fixed series compensation for single line to ground fault at rectifier bus II

4 9   DC line fault

The response of the system with delta regulator for this fault is given in Figures 4 25 4 26 Delta regulator works satisfactorily for this
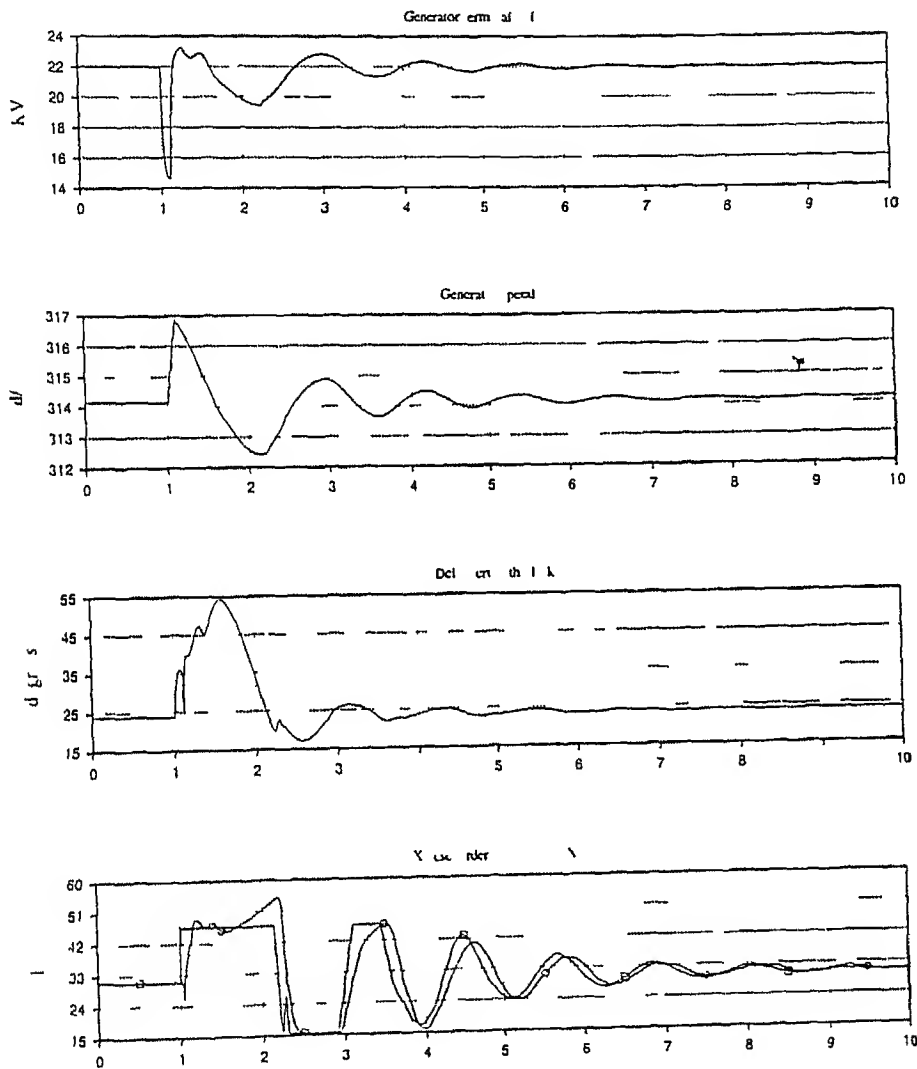

Figure 4 25 System response with TCSC delta regulator for DC line fault   I

For all the DC faults (AC converter bus or DC line) the power quickly reduces to zero because of the collapse of the voltage So the power controller output (current order) hits its maximum limit in this case 2 5 KA But the VDCOL action prevents
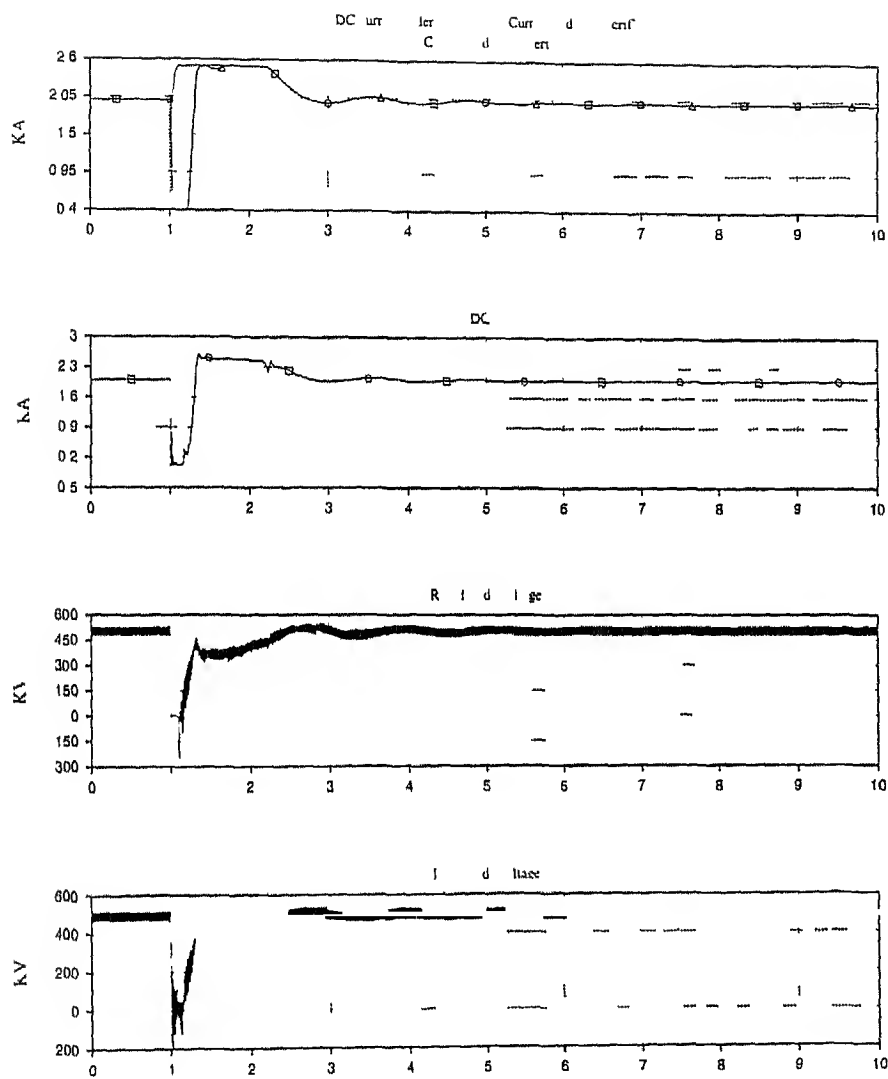
Figure 4 26 System response with TCSC delta regulator for DC line fault II

this increased current order going to the current controllers VDCOL reduces the current order actually sent to the current controller due to low voltages

4 10 Three phase solid fault at the TCSC terminals

The response of the system with delta regulator for the fault at first terminal(bus5) is given by Figure 4 27 and the second terminal(bus6) is given by the Figure 4 28 Delta regulator works satisfactorily for both cases

4 11 Rejection of local load in the generating area

The 1000 MW local load connected at the generating area is rejected fully for 20 cycles The response of the system with delta regulator for this is given in Figures 4 29 4 32

The system with fixed series compensation loses stability for this load rejection as seen from Figures 4 33 4 34

4 12 Step changes in DC power reference

The delta regulator is able to deal with the changes in the DC power reference Figure 4 35 shows the system response for multiple changes in DC power reference The step changes given are 200 MW at t=1sec +400 MW at t=6 sec 400 MW at t=11 sec and +200 MW at t=16 sec It is seen that after a very small transient, delta returns to its reference value,which is $23\ 8^0$ here Also it is seen that in DC line power there are hardly any transients DC power flow changes almost instantaneously The system transients are reflected in AC line
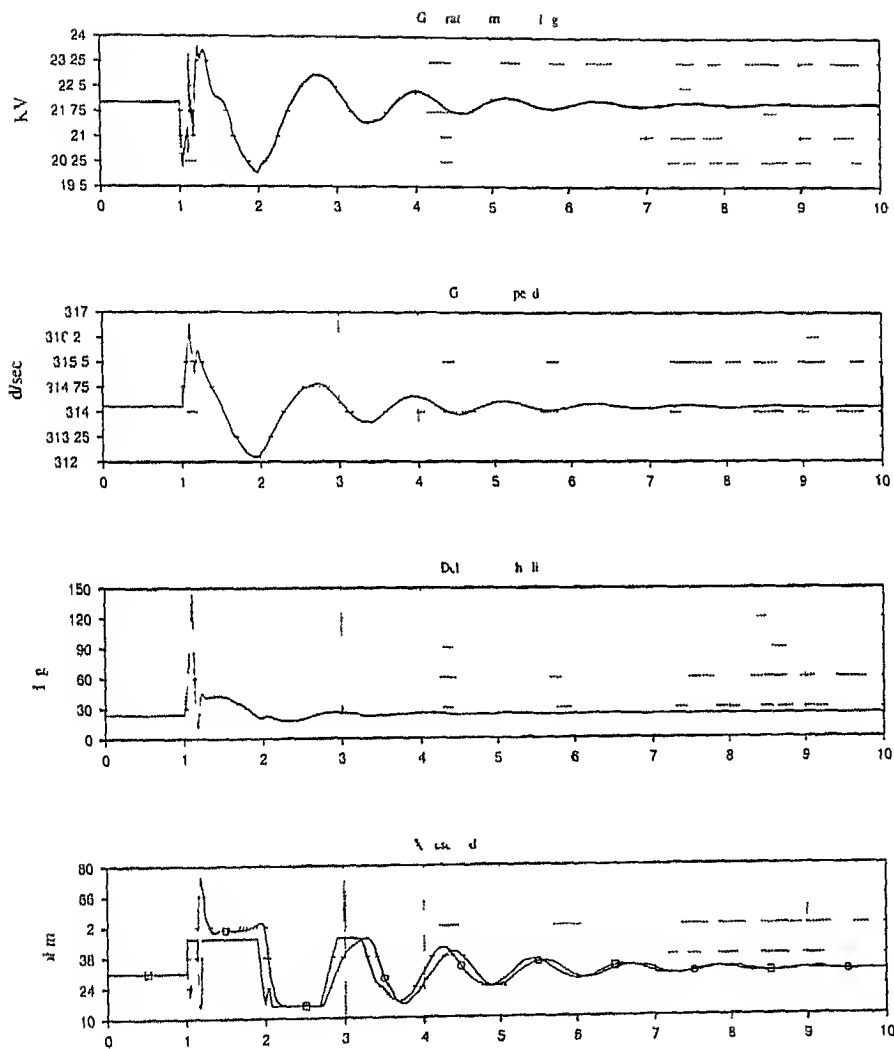
Figure 4 27   System response with TCSC delta regulator for 3 phase fault at the first TCSC terminal (bus0)
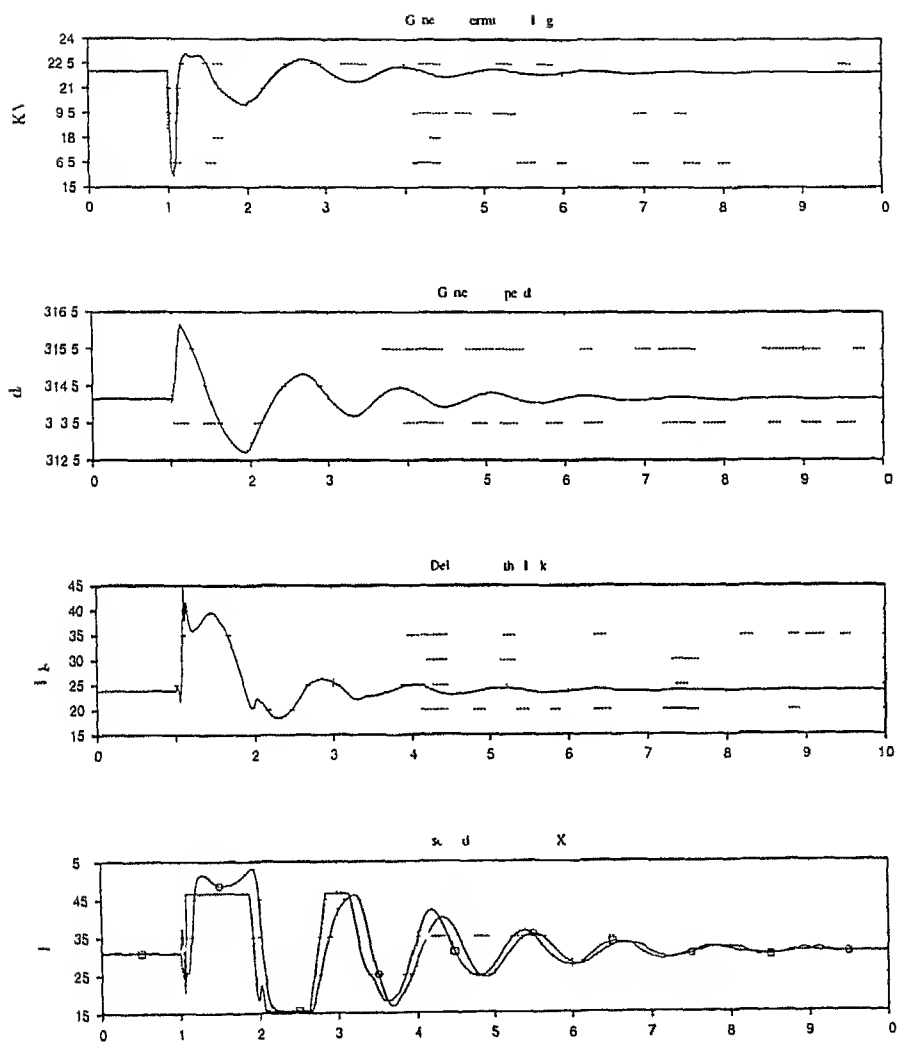
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Figure 4 28 System response with TCSC delta regulator for 3 phase fault at the second TCSC terminal (bus6)

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Figure 4.29 System response with TCSC delta regulator for local load rejection at the generating area 1
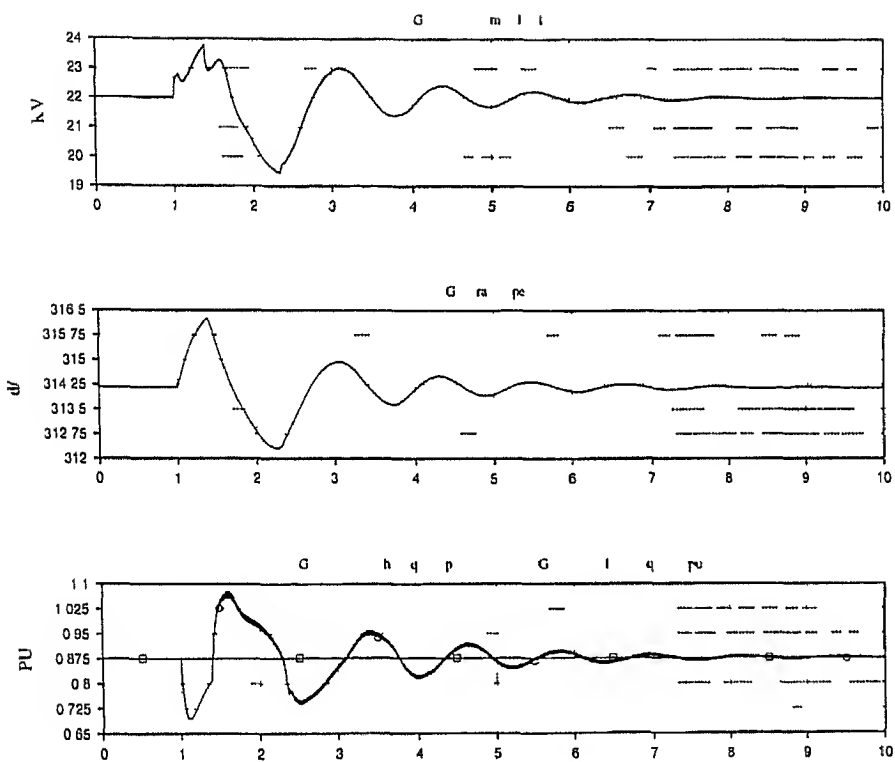
Figure 4 30 System response with TCSC delta regulator for local load rejection at the generating area II

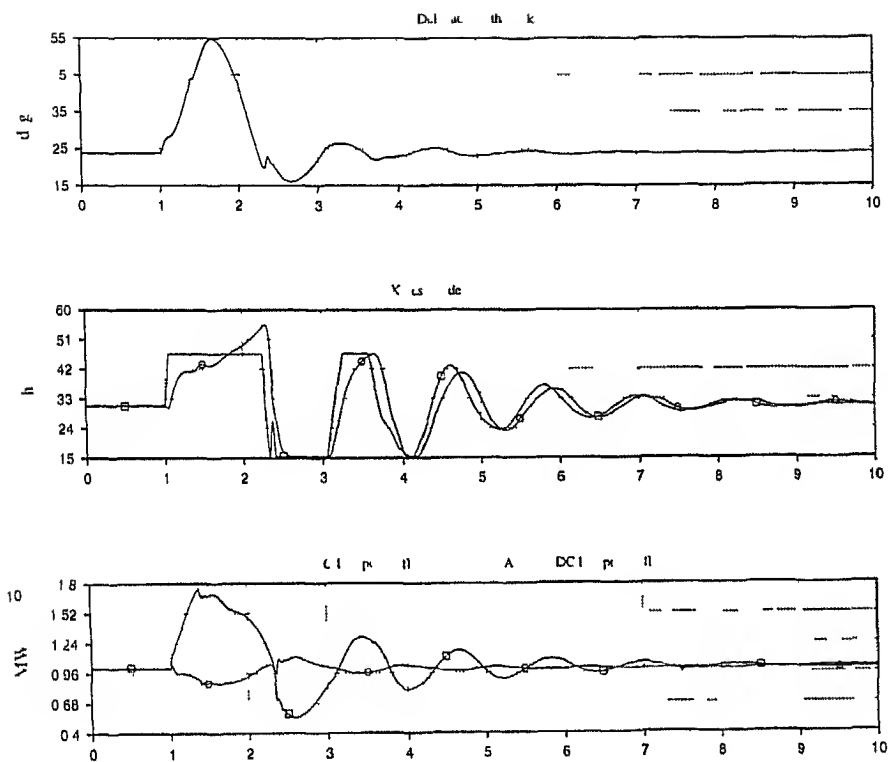Figure 4 31 System response with TCSC delta regulator for local load rejection at the generating unit III

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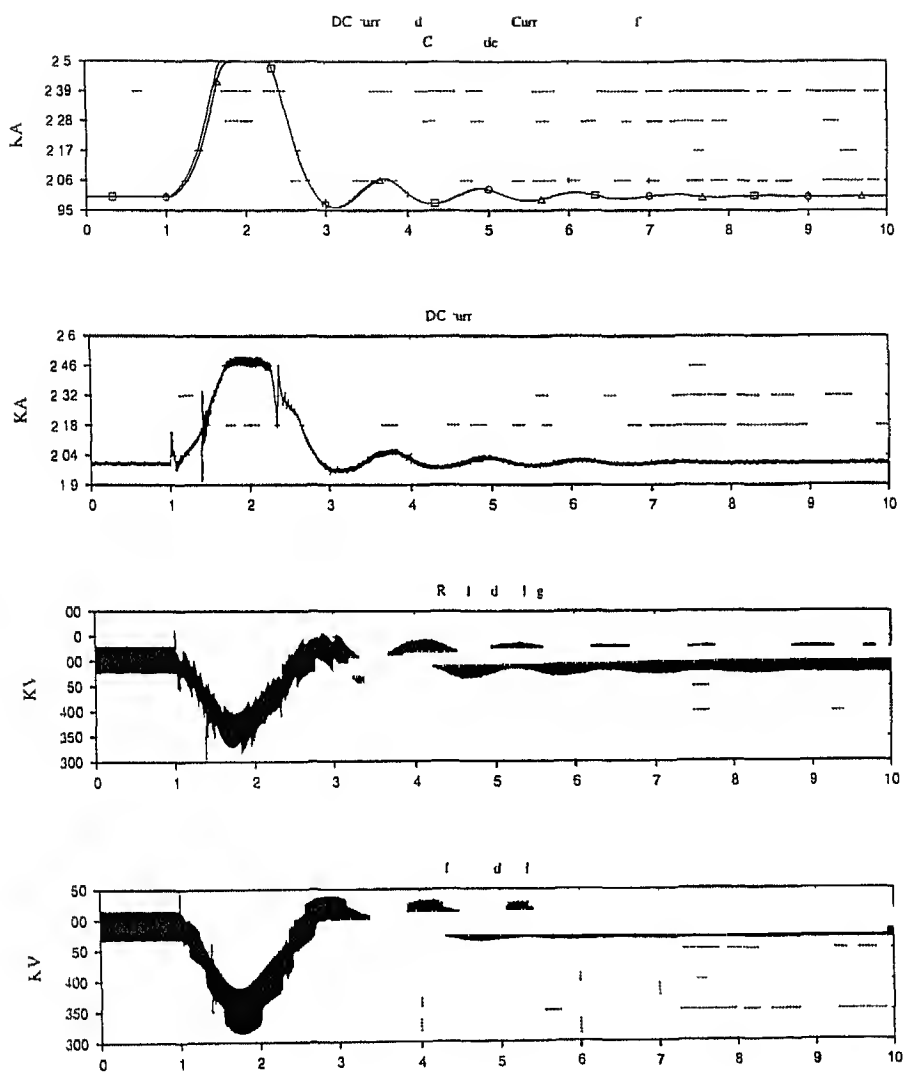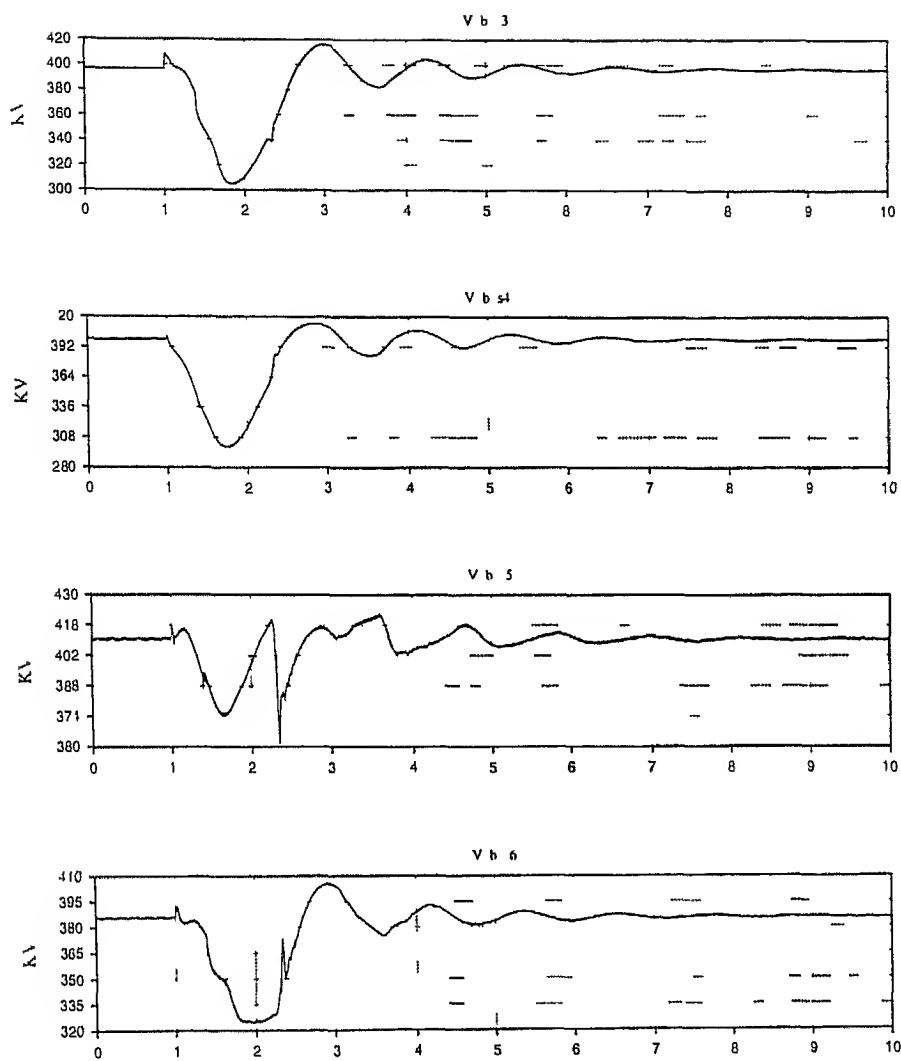Figure 4 32 System response with TCSC delta regulator for local load rejection at the generating unit IV
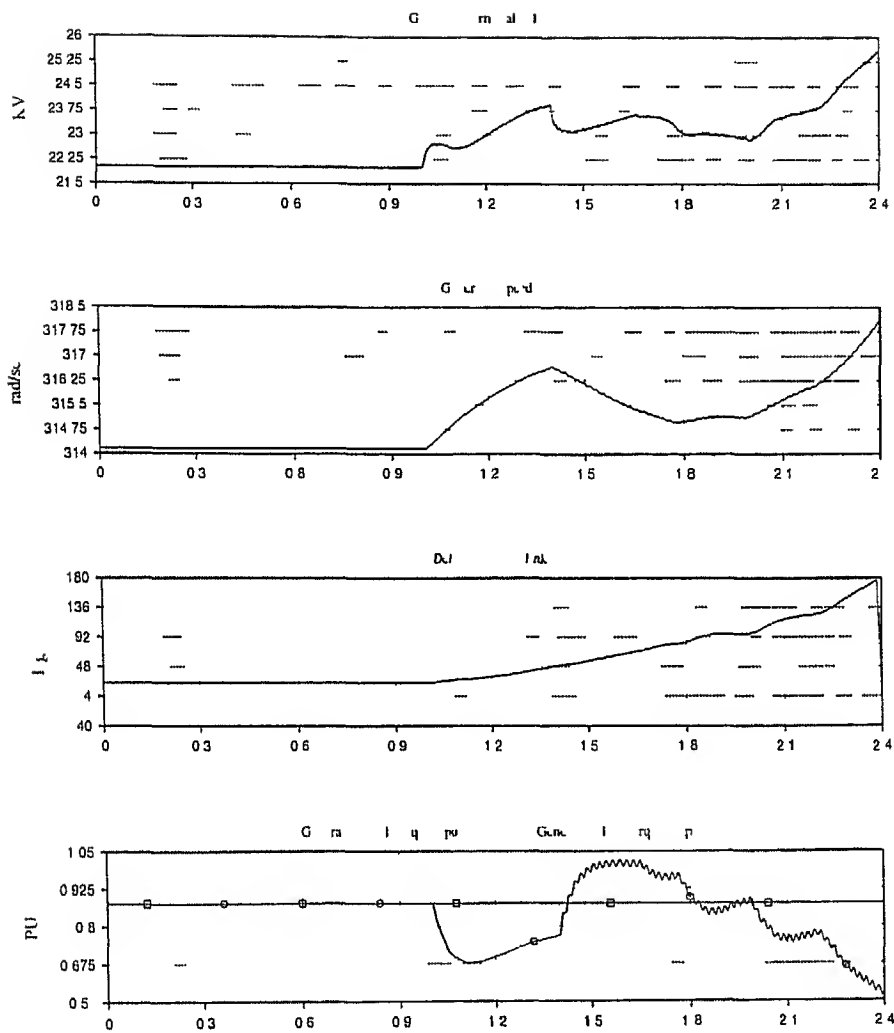
Figure 4 33 System response with Fixed series compensation for local load rejection at the generating unit I
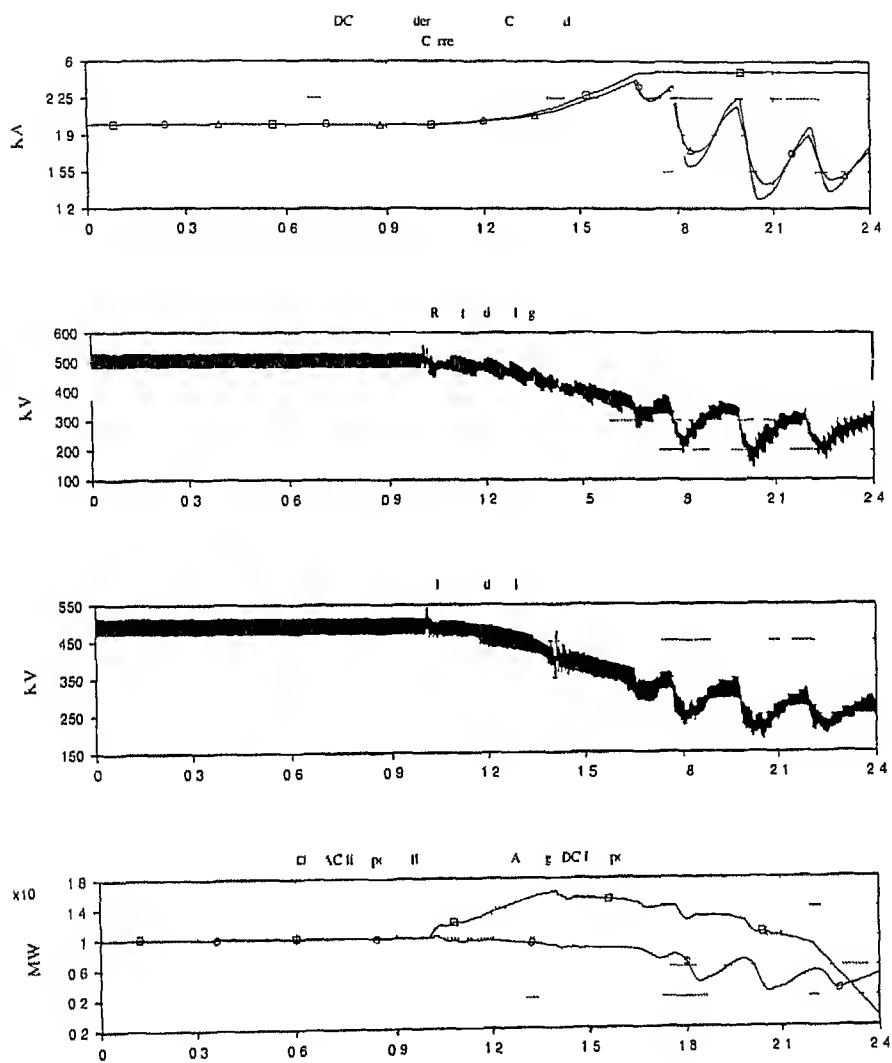
Figure 131 System response with fixed series compensation for local load rejection at the generating area II
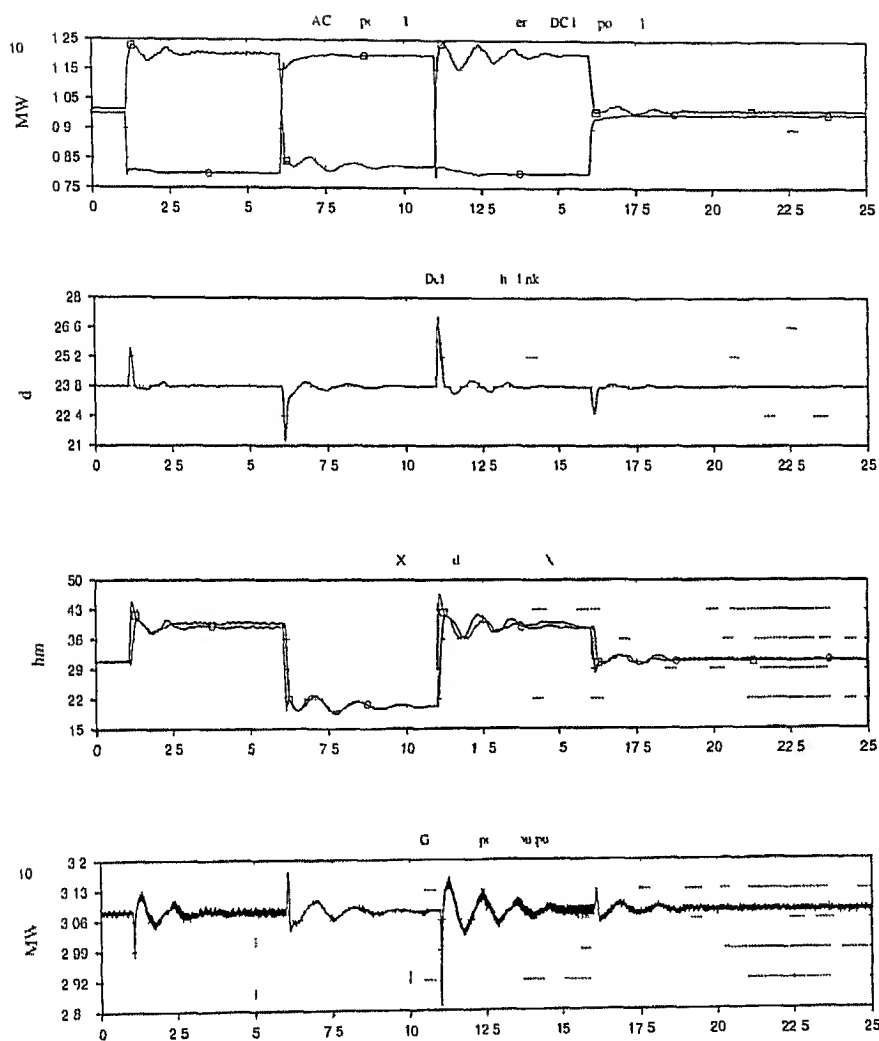
Figure 4 35 System response for multiple changes in DC power reference

4 13 Step changes in Delta reference

The delta regulator is subjected to multiple reference changes at t=1 sec (-5^0) t=6 sec (-10^0) t=11 sec (-10^0) and t=16 sec (-5^0) The delta regulator is able to track the reference value But the response is more oscillatory compared to case of step changes in DC power reference Figure 4 36 shows the response for these changes
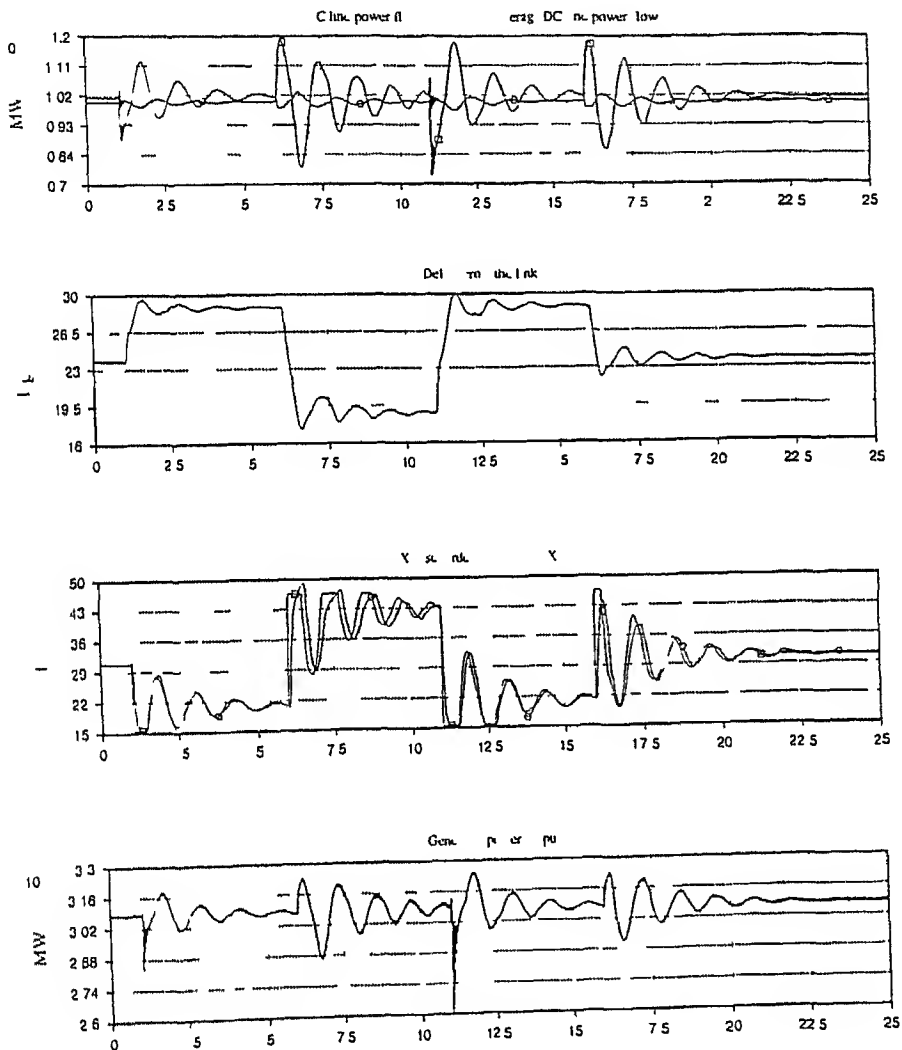
Figure 4 36 System response for multiple changes in delta reference

4 14 Step chan₂, ₁ ₁ mechanical power input of the genera⁻oı

The generator is given a step changes mechanical power input For a −o% change system response is shown in Figure ' 3ı For a 5% change system response is shown in Figure 4 38 After some oscillations the value of delta returns to it reference value
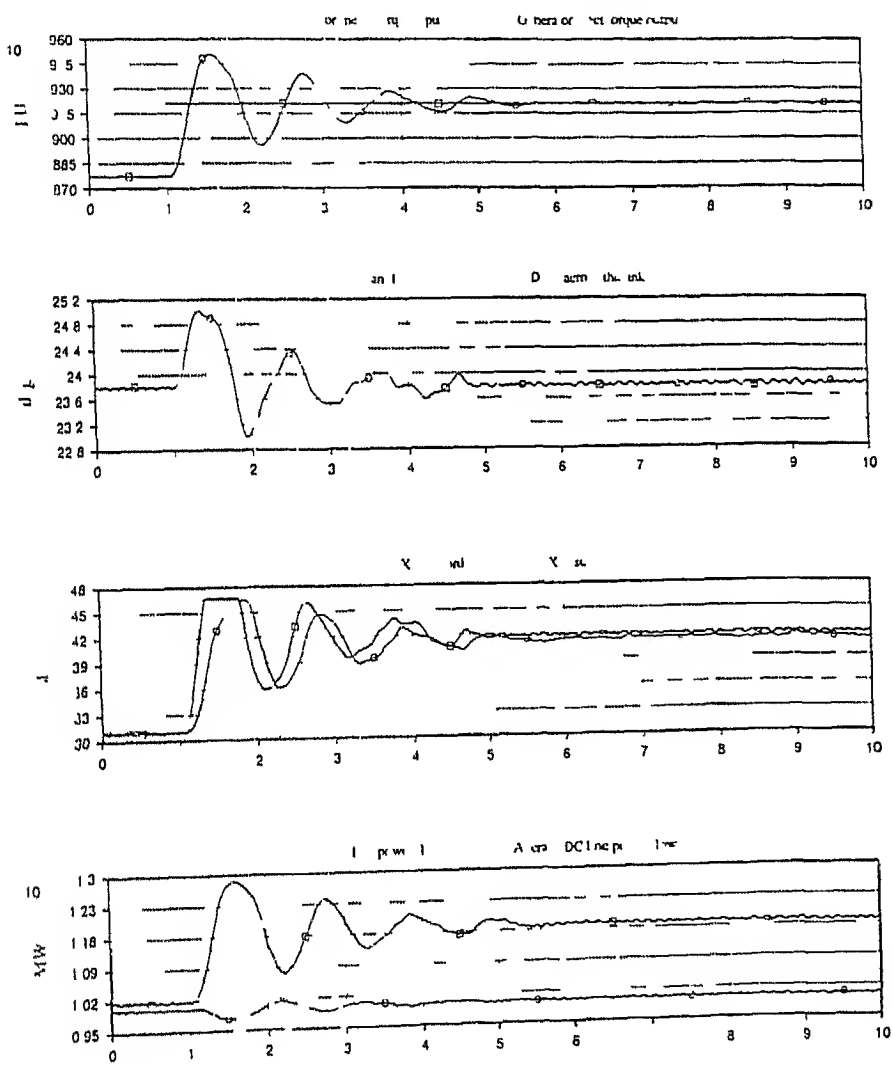
Figure 1 37 System response to 1 o% step increase in mechanical power input of the generator

Figure 4 38 System response to a 5% step decrease in mechanical power input of the generator

73

Chapter 5

Conclusions

The main aim of this thesis was to develop for a parallel AC DC link a control strategy for variable series compensation of the AC line and to assess the performance of this control strategy. The device used for variable series compensation is TCSC(Thyristor Controlled Series Capacitor). The power system has been represented by a single generator connected to an infinite bus through a network which has an embedded parallel AC DC link.

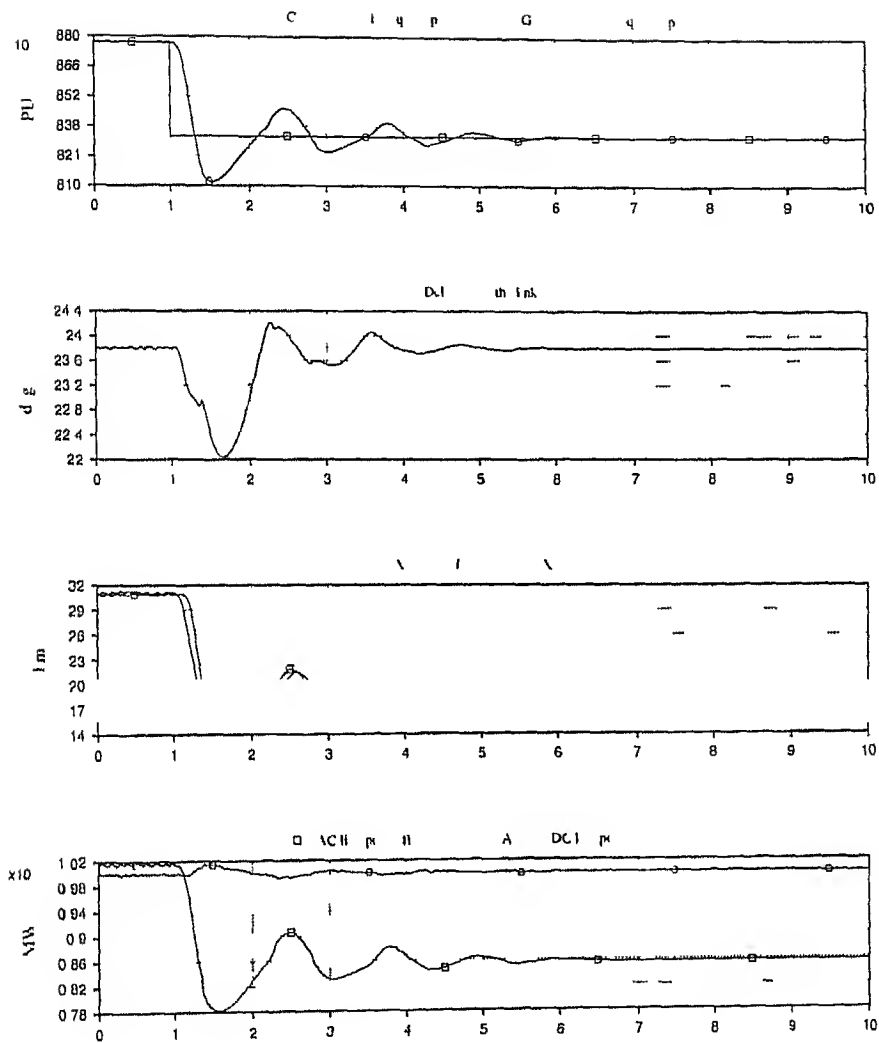It is demonstrated that the control strategies for the DC link and variable series compensation cannot work in isolation and the controllers on both need to be co ordinated either explicitly or implicitly. Here a control strategy is proposed for variable series compensation which does not come in conflict with the DC link controls or the rest of the system and there is implicit co ordination. The DC link controls the power. The controller proposed for variable series compensation regulates the power angle (delta) across the parallel link. The controller proposed here can be realised with use of local measurements only.

The system was subjected to a wide range of disturbances to assess the performance of the control strategy. The disturbances simulated includes faults applied at various locations in the network and step changes in the power angle reference, DC link power reference and mechanical power input of the generator. The delta controller shows a marked improvement in the transient stability of the system. In all cases, it improves the stability margin compared to a system with a fixed series

compensation on the AC line. The control design was found to be robust. It works satisfactorily under all conditions.

5 1   Suggestions for further work

1 In the present work, the main controller for variable series compensation is designed. This improves the transient stability of the system but the damping of the system for oscillations is found to deteriorate. The small signal modulation of the variable series compensation is a very powerful tool for improving the damping of the system. An auxiliary control for this can be designed as further work. For this TCSC dynamics need to be represented fully.

2 The controller designed here shows very small magnitude oscillations in output. This is because of the high gain values used and fourth order TCSC response which is basically a lag. Proper lead lag compensation needs to be designed to eliminate these oscillations.

3 In some cases reactive compensation for the HVDC link may be provided by SVC(Static VAR compensator). The SVC and TCSC interaction can be studied for such a case.

4 Here the TCSC works in capacitive mode only. If a firing control is designed which is able to shift TCSC operation into inductive mode as well, it will further improve the transient stability.

Appendix A

System data

A 1   Base case load flow

Generator bus angle = 56 12^0

Generator real power output = 3080 MW

Generator reactive power output = 600 MVAR

Real power supplied to infinite bus = 1940 MW

Reactive power supplied to infinite bus = 226 MVAR

AC line power flow = 1000 MW

DC line power flow = 1000 MW

Rectifier bus voltage = 396 6 KV

Rectifier converter transformer tap setting = 1 075

Inverter bus voltage = 399 4 KV

Inverter converter transformer tap setting = 1 040

$\alpha_{rectifier} = 15\ 5^0$

$\gamma_{inverter} = 15^0$

$\alpha_{inverter} = 141\ 6^0$

A 2 Generator data

A 2 1 Machine data

Ratings 22 kV 3750 MVA

P U values given are on generator base

$R_a = 0.0025$ pu, $X_a = 0.2$ pu

$X_d = 0.8$ pu, $X_d' = 0.3$ pu $X_d'' = 0.25$ pu

$X_q = 0.6$ pu, $X_q'' = 0.25$ pu

$\tau_{do}' = 7.0$ sec $\tau_{do}'' = 0.03$ sec $\tau_{qo}'' = 0.06$ sec

$H = 1.0$ MW s/MVA

Friction and windage losses $= 0.05$ pu

A 2 2 Exciter data

Exciter type is exc35

Voltage measurement time constant $= 0.02$ sec

Controller lead time constant $= 1.5$ sec

Controller lag time constant $= 1.0$ sec

Exciter gain $= 100$

Exciter time constant $= 0.02$ sec

$E_{fDmin} = 5$ pu $E_{fDmax} = 5$ pu

A 2 3 Power system stabiliser data

Number of lead lag blocks used $= 3$

Lead time constant $= 0.179$ sec

Lag time constant $= 0.1916$ sec

Washout block time constant $= 10.0$ sec

A 3 Transformer data

Transformer at generator end

3750 MVA 22/400 KV $X_l = 0.1$ pu on its own base

Transformer at infinite bus end

2500 MVA 100/230 KV $X_l = 0.1$ pu on its own base

Converter transformers at rectifier

600 MVA 100/200 KV $X_l = 0.15$ pu on its own base

Converter transformers at inverter

600 MVA 400/200 KV $X_l = 0.15$ pu on its own base

A.4   Transmission line data

A.4.1   Transmission line parameters

Resistance $= 0.01\ \Omega/\text{km}$

Inductive reactance $= 0.1554\ \Omega/\text{km}$

Capacitive reactance $= 0.13866\ \text{M}\Omega\ \text{km}$

A.4.2   Transmission line lengths

From generator to the parallel link 200 kms

For AC link 800 kms

From parallel link to infinite bus 200 kms

A.5   TCSC Data

A.5.1   Component values

$L = 15$ mH

$C = 201.83\ \mu\text{F}$

Inductor value for shunt compensation at TCSC terminals $= 2.206842$ Henry

A.5.2   TCSC Controller

$G_p = 5.0$

$G_i = 50.0$

$X_{orderMin} = 15.51$ Ohms

$X_{orderMax} = 16.62$ Ohms

A.6 HVDC controls

A.6.1 Current control

Base current = 2 Amps

$G_p = 3.0$ deg/amp s

$G_i = 0.01$ pu

$\alpha_{max} = 110^0$

$\alpha_{min} = 5^0$

A.6.2 Gamma control

$G_p = 0.1$ pu

$G_i = 10.0$ pu

$\alpha_{max} = 164.95^0$

$\alpha_{min} = 100^0$

$\gamma_{minOrder} = 15^0$

incremental current level = 0.4 pu

current fade out time constant = 0.02 sec

A.6.3 Power control

$I_{orderMax} = 1.25$ pu

$I_{orderMin} = 0.20$ pu

Voltage measurement time constant = 0.2 sec

Minimum limit on measured voltage = 400 kV

Current order application time constant = 0.02 sec

A 6 4   VDCOL

$V_{h} = 0.7$ pu

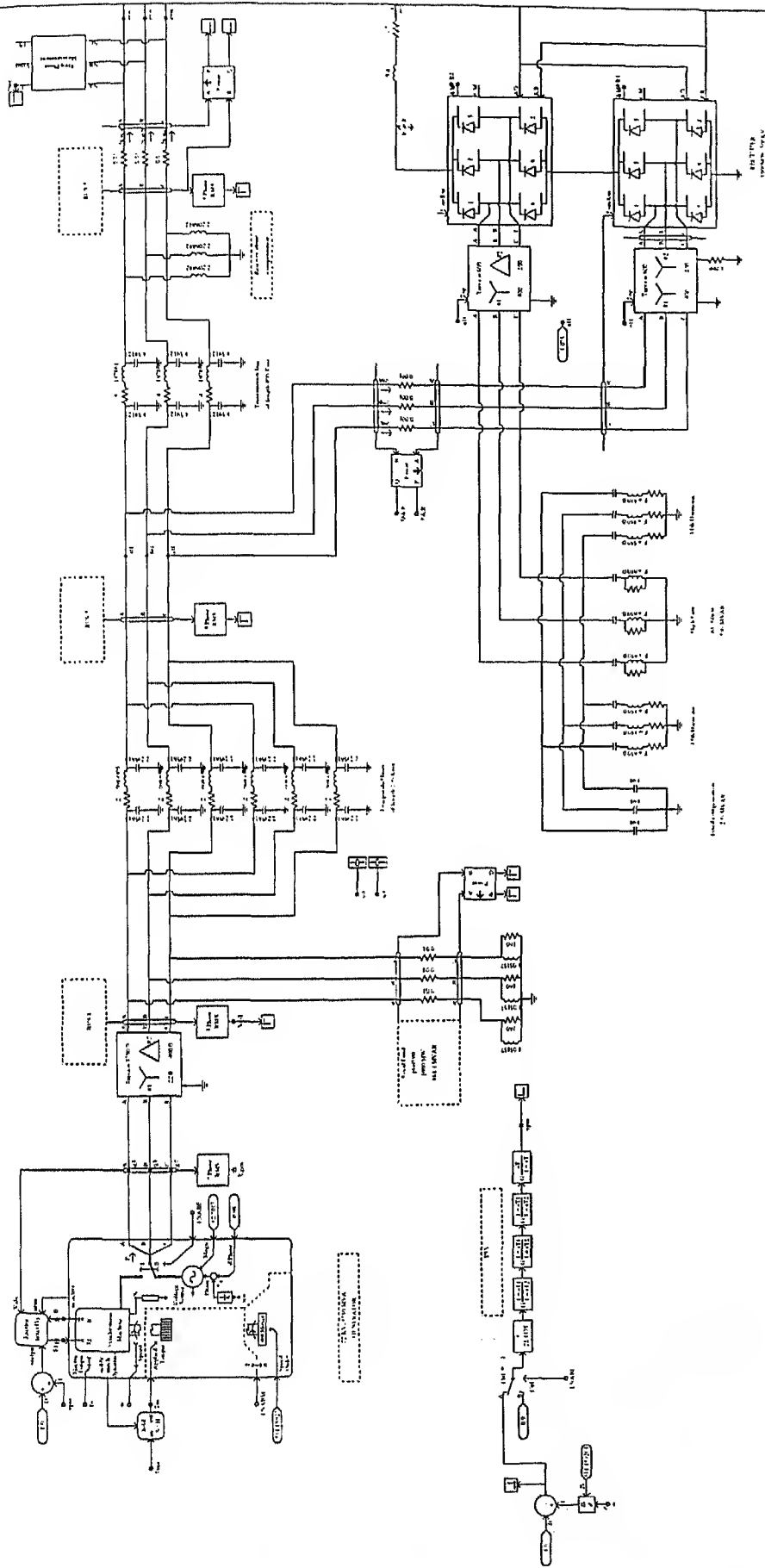$V_{ll} = 0.2$ pu

$I_{min} = 0.2$ pu

Lag time constant $= 0.02$ sec

Current order recovery rate $= 25$ pu/sec

Appendix B

PSCAD draft files

Here PSCAD draft files are given

IIT Kanpur, INDIA
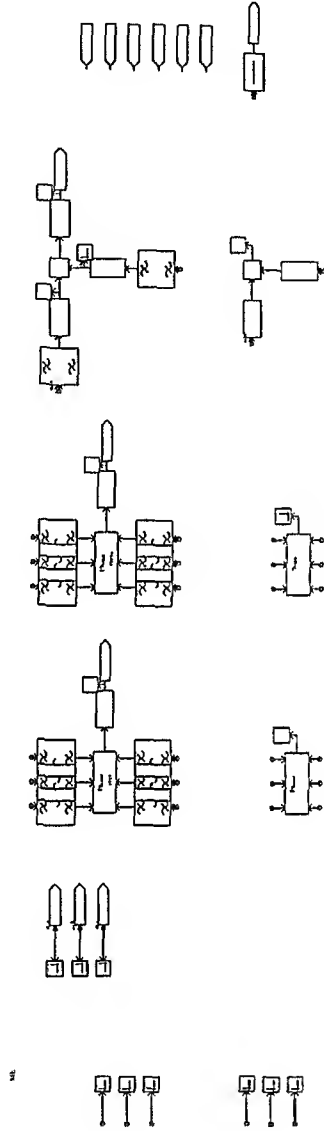
TWO AREA SYSTEM

Created:	October 10, 1996 (alokm)
Last Modified:	February 25, 1997 (alokm)
Printed On:	February 25, 1997 (alokm)

ELECTRICAL

ELECTRICAL SYSTEM

Subsystem #1 of 2

IIT Kanpur, INDIA

TWO AREA SYSTEM

Created:
Last Modified:
Printed On:

October 10, 1996 (alokm)
February 25, 1997 (alokm)
February 25, 1997 (alokm)

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	Printed On	Feb u m 25 1997 (alt k n)	Subsystem #1 of 2

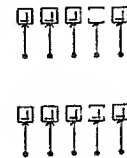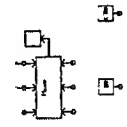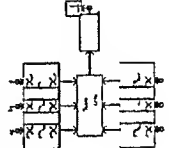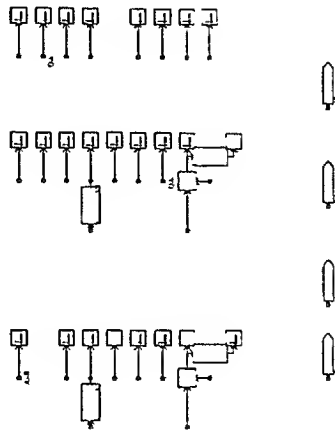|	
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ELECTRICAL SYSTEM
Subsystem #1 of 2

IIT Kanpur INDIA
TWO AREA SYSTEM

IIT Kanpur INDIA
TWO AREA SYSTEM

Created	October 10 1996 (alokm)
Last Modified	February 25 1997 (alokm)
Printed On	February 25 1997 (alokm)

CONTROLS
CONTROLS FOR DC & TCSC
Subsystem #2 of 2

IIT Kanpur INDIA	Cre ted	October 10 1996 (alt km)	CONTROLS
TWO ARLA SYSTEM	Last Modified	February 25 1997 (alokm)	CONTROLS FOR DC & ICSC
	Printed On	February 25 1997 (alokm)	Subsystem #2 of 2

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